Status of the R&D activities to the design of an ITER core CXRS diagnostic system

Citation for published version (APA):

DOI:
10.1016/j.fusengdes.2015.05.039

Document status and date:
Published: 01/10/2015

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 14. Sep. 2020
Status of the R&D activities to the design of an ITER core CXRS diagnostic system

Philippe Mertens a,⁎, David A. Castaño Bardawil a, Tétény Baross b, Wolfgang Biel a, Sebastian Friese a, Nick Hawkes c, Roger J.E. Jaspers d, Vladislav Kotov a, Yury Krasikov a, Andreas Krimmer a, Andrey Litovskiy a, Oleksander Marchuk a, Olaf Neubauer a, Guido Offermanns e, Anatoly Panin a, GergóPokol f, Michael Schrader a, Ulrich Samm a

a Institute of Energy and Climate Research IEF-4 (Plasma Physics), Forschungszentrum Jülich (FZJ), Trilateral Euregio Cluster, D-52425 Jülich, Germany
b Wigner Research Centre for Physics (Wigner RCP), HU-1121 Budapest, Hungary
c Culham Centre for Fusion Energy (CCFE), Culham OX14 3DB, United Kingdom
d Eindhoven University of Technology (TU/e), PO Box 513, NL-5600 MB Eindhoven, The Netherlands
e Zentralinstitut für Engineering, Elektronik und Analytik ZEA-1 (Engineering and Technology), FZJ, Trilateral Euregio Cluster, D-52425 Jülich, Germany
f Budapest University of Technology and Economics (BME), HU-1111 Budapest, Hungary

HIGHLIGHTS

• The CXRS diagnostic for the core plasma of ITER will provide observation of the dedicated diagnostic beam (DNB) over a wide radial range, roughly r/a = 0.7 to 0.
• A high performance (étendue × transmission, dynamic range) is expected for the port plug system since the beam attenuation is large and the background light omnipresent.
• The design is particularly challenging in view of the ITER environment, especially with respect to the first mirror which faces the plasma.
• The current status of development is presented by detailing several sub-systems before a four years design phase under an FPA between F4E and the ITER core CXRS Consortium (IC3).

ARTICLE INFO

Article history:
Received 19 September 2014
Accepted 20 May 2015
Available online 3 September 2015

Keywords:
ITER
Diagnostic
Active spectroscopy
Upper port plug
CXRS
Charge-exchange

ABSTRACT

The CXRS (Charge-exchange Recombination Spectroscopy) diagnostic for the core plasma of ITER will be designed to provide observation of the dedicated diagnostic beam (DNB) over a wide radial range, roughly from a normalised radius r/a = 0.7 to close to the plasma axis. The collected light will be transported through the Upper Port Plug #3 (UPP3) to a bundle of fibres and ultimately to a set of remote spectrometers. The design is particularly challenging in view of the ITER environment of particle, heat and neutron fluxes, temperature cycles, electromagnetic loads, vibrations, expected material degradation and fatigue, constraints against tritium penetration, integration in the plug and limited opportunities for maintenance. Moreover, a high performance (étendue × transmission, dynamic range) is expected for the port plug system since the beam attenuation is large and the background light omnipresent, especially in terms of bremsstrahlung, line radiation and reflections. The present contribution will give an overview of the current status and activities which deal with the core CXRS system, summarising the investigations which have taken place before entering the actual development and design phase.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The core Charge-Exchange Recombination Spectroscopy diagnostic (CXRS) for ITER will be installed in an upper port plug (UPP 3) and shall observe the dedicated diagnostic beam (DNB) in the next sector in anti-clockwise direction. It is expected to measure and derive several physical quantities from the light emitted as a result of the interaction of the neutrals in the diagnostic beam with impurity ions in the plasma. It seemed appropriate to summarise the status of development reached before entering a four years design phase under the umbrella of a Framework Partnership Agreement (FPA) between...
the European Agency F4E and the ITER core CXRS Consortium (IC3).

The core CXRS diagnostic will be designed to provide observation of the DNB over a wide radial range, roughly from \( r/a = 0.7 \) to close to the plasma axis (with \( r/a \) the radius normalised to the minor plasma radius \( a \)). The collected light will be transported by a bundle of fibres to a set of remote spectrometers. The design is particularly challenging in view of the ITER environment of particle, heat and neutron fluxes, temperature cycles, electromagnetic loads, vibrations, expected material degradation and fatigue, constraints against tritium penetration, integration in the plug and limited opportunities for maintenance [1,2].

The first mirror which is facing the plasma is obviously the most vulnerable component. It is subjected to simultaneous erosion and deposition of impurities which may reduce the specular reflectivity significantly. A high performance in terms of étendue \( \times \) transmission or dynamic range is expected, though, since the beam attenuation is large and the background light omnipresent, especially from bremsstrahlung, line radiation and reflections. As a consequence, a shutter is foreseen to protect the mirror from the particle fluxes when no measurement is taking place.

Engineering studies were conducted on several concepts and on specific components like the above-mentioned shutter, retractable tubes, mirrors and mirror mounts, calibration systems, etc. They cover the optical design, electromagnetic, structural and thermal analysis of single components and assemblies and lead to preliminary performance assessments. Details are given in numerous separate, specialised contributions. The several functional elements of a possible diagnostic arrangement have reached different stages of development.

2. Spectral range

The core CXRS system is an active spectroscopic diagnostic which measures line emission of several highly ionised impurities in the plasma. The light emission is triggered by the capture of an electron from the neutral hydrogen atoms in the injected diagnostic beam. This charge exchange leaves the resulting H-like impurity ion in an excited state, which is stabilised by emitting light.

The physical quantities to be measured encompass the core He density, the concentration and/or the density and temperature profiles of several impurity ions and, to some extent, the plasma rotation. The detection limits (minimum density, time and spatial resolution) may be different for all these quantities and very much depend on the profile and available current density of the DNB. A summary of the requirements is given, for instance, in [3].

The corresponding spectral range, which forms the basis of the optical design, can be roughly split in the visible in

- a \( \lambda 460 \) nm band (He, Be) – around 468 nm which enables observation of He II, Be IV;
- a \( \lambda 520 \) nm band (C, Ne, Ar, Kr) – around 527 nm, for Ne IV, Be II, Ne X and Ar XVII/XVI; and
- a \( \lambda 656 \) nm band (Balmer) with \( \text{H}_\alpha, \text{D}_\alpha, \text{T}_\alpha \) at 656 nm.

The system is thus designed for the visible spectral range with the blue region, from 450 nm up, the most difficult to achieve but also the most important one. The design will be based on recent physics and instrumental developments as found in [3–6].

3. Functional assemblies and analysis

A possible arrangement of the CXRS port plug UPP 3 is depicted in Fig. 1.

The whole setup is embedded in the port plug container which also hosts other diagnostic systems. In the present case, it is a wall conditioning antenna with its feeding lines. Similarly, the Diagnostic First Wall (DFW), the Diagnostic Shield Module (DSM) at the front and the volume for a rear assembly at the back are given parts of the generic port plug.

Several building blocks or sub-systems of the CXRS diagnostic can readily be identified on the picture. The list comprises, according to a functional breakdown: the entrance aperture and optical duct, the front mirror assembly, the first mirror (M1) protection shutter, the M1 cleaning device (not part of the current FPA), the rear mirror assembly, the calibration system and, behind the vacuum windows, the external components like the light transport system made of glass fibres, the spectrometers and sensors, the data-acquisition system. Alternatively, the imaging and light transport system in the port plug can be split from another point of view, i.e. according to the demanding environmental requirements, in a first mirror M1 and a catadioptric chain of subsequent optical elements, composed mostly if not exclusively of mirrors M2…Mx.

The thermal, thermo-mechanical, full structural and electromagnetic analysis of several components of the last but one option can be found in [7–13].

3.1. The optical duct

The optical duct is obviously an indispensable penetration through the diagnostic first wall, which influences the actual positioning of the water channels which ensure the active cooling. The exact shape will depend on the optical design but it is likely that the entrance hole (most probably the entrance pupil of the optics) must and can be kept with a diameter \( D \) between 025 mm and 045 mm. The current target is to withdraw the first mirror by a distance \( L \) such that \( L/D > 5 \). Experimental investigations are pursued, some of which are reported on in [13]. A long conical duct – the longer the better – with an integrated system of baffles can be mandatory, both to reduce stray light and the effect of impinging particles, sputtering and deposition [14]. Similarly, the length of the duct and the layout of the baffles can significantly improve the heat flux incident on the first mirror; a recent detailed analysis in the case of purely radiative loads can be found in [15]: the flux density can be reduced from an impinging order of magnitude of 200 kW/m² to about 400 W/m² depending on the assumed emissivity of the duct walls and on their temperature, that is on the efficiency of the local active cooling. Note that this dramatic reduction applies only to the radiative case and is also dependent on the temperature which can be assumed for M1 as well, so it very much depends on the actual design. The estimation was performed for a large mirror option as shown in Fig. 2.
3.2. The fast shutter

The shutter is the most straightforward protection which can be implemented to protect the first mirror and increase its lifetime to sensible values between cleaning operations. For this reason, it was so far one of the mostly studied components [10,11,16–18]. Multi-field (thermal, electromagnetic and structural) analysis for the previous shutter options [10,16] resulted in the baseline design within IC3, a frictionless fast shutter which can be operated at opening and closing speeds compatible with the characteristic times of the DNB modulation. Reaction times (full opening or closing) below 0.7 s are expected. The main shutter requirements are:

- mirror protection except for the measurements when full opening to mirrors is provided (the highest possible protection is guaranteed during dwell time, baking or torus maintenance phases);
- to require a minimum cut-out in the DFW or neutronic shielding;
- to withstand the thermal, EM and seismic loads;
- to operate for the full ITER lifetime without maintenance.

The shutter is equipped with two long arms (∼2 m long), a gas actuator (up to 5 bars) and a set of bumpers that restrain the lateral and axial movements of the arms (Fig. 3). The force exerted by a gas actuator makes the shutter arms bend laterally between two pairs of bumpers to open or shield the optical aperture. After the arms first hit the bumpers, they start to bounce and oscillate. This might deteriorate the mirror measurements and protection.

As usual, the complex FE dynamical analysis is preceded by static and modal analyses. They highlight the main structural features like important natural modes contributing to the dynamic response, and give reasons for a choice of strategy and assumptions used in the dynamic modelling.

The required static operational force (close/open shutter) coming from the He gas actuator was defined (∼5 kN). Important natural modes are given in Fig. 4.

The first one (∼5 Hz) contributes to the arms lateral movement between bumpers. The third mode is responsible for the arms vertical oscillations. The fourth one determines oscillations of the arms (with blades) around the bumpers. The first two modes, being in the low frequency range of 5–11 Hz, seem dangerous from the seismic point of view. But it is important to note, that a high-energy and low-frequency structural response corresponding to these modes is not possible for the arms since their lateral movement is restrained by the bumpers. When the arms reach the bumpers, the system stiffness becomes higher. Its dynamic response changes and causes only a high-frequency- and low-amplitude-movements. So, no high mechanical stresses develop in the structure. The seismic analysis for the previous shutters did not reveal any serious problems. Note that additional bumpers may be implemented if needed to prevent the excessive vertical shutter deformation under seismic load.

Fig. 3. Detailed model of the baseline shutter (disregard the support which is foreseen in this form only for the prototype).

Both an explicit and implicit 3D FE transient structural modelling was used to study the dynamic behaviour of the shutter [19]. Fig. 5 shows movements of the protective blades for different actuation scenarios. A simple 1D analytical model was developed to predict the shutter dynamic response. The structure sensitivity to different parameters (like shutter stiffness, natural modes, actuator pressure time profile, etc.) was examined in detail and ways for the shutter optimisation were clarified.

Two shutter prototypes will be needed. The first one, a full-scale is under manufacturing. It will be tested in air and in a vacuum chamber to optimise the mechanical layout and the actuator gas loop system. Designed to meet the severe ITER environment, it is made in a full-scale complexity to check its manufacturability and achievable tolerances [20]. The other one is a parametric, simplified mock-up with easily changeable mechanical characteristics like stiffness and mass. It allows for a variation of the shutter stiffness, its natural frequencies and initial preload [21]. Both shutters use the same actuator. Fig. 6 shows the arm layouts for this simplified parametric shutter.

The mechanical performance of both shutters, initially designed to be similar, is now somewhat different due to changes during the detailed design and manufacturing phases (see [20] and [21] for details). A test programme aimed for further shutter optimisation, basing on the analysis performed and engaging the powerful capabilities of the parametric shutter mock-up has been established in [19,21].

Besides recommendations for optimisation, a tentative test programme will be defined, especially with respect to the stiffness of the shutter arms. The impact of geometrical deviations as they can occur as a result of manufacturing inaccuracies is assessed in [21]: deviations in the order of a 1–2 mm do not modify frequencies or preloads by more than 2–3%. Such investigations give confidence that, if a simplified prototype can be built successfully, the concept of a frictionless fast shutter can be adapted to new optical designs which may be quite different from the baselines given in [22,23]. Note that the estimated lifetime of the pneumatic actuator amounts to >10^6 cycles on average for operating temperatures around 100°C and pressure rise/decrease values from 0 to 5 bar within the given 0.7 s.

![Fig. 4. Natural frequencies of the shutter arms (see also [19] for details).](image4.png)

![Fig. 2. Configuration analysed with ANSYS in [15].](image2.png)
3.3. The first mirror (M1)

The first mirror is the next mostly investigated item. It plays a special role because it is exposed in a direct line of sight to the plasma. This drawback may require the selection of a particularly resistant mirror material, at the expense of the desirable high reflectivity. The choice of a single-crystal molybdenum mirror (ScMo) was studied most in the last years and is the reference candidate. The major aspects of these investigations are quoted in [24], based on the design discussed in [23]. Since the limited lifetime of M1 may become an insuperable obstacle, both a fast shutter and a cleaning system are deemed indispensable at the present time, notwithstanding the presence of an optimised duct as elaborated on in Section 3.1.

Several options are considered in [24], mainly in two classes: the passively cooled mirrors, which might reduce the deposition effects but were mostly intended for a carbon machine, and the actively cooled options.

The passively cooled mirrors are maintained at temperatures up to 300–350 °C. The anisotropic temperature distributions and thermo-mechanical deformations may lead to total deformations of up to 30 μm at the tip, which can be compensated for by a robust optical design. Moreover, the availability of ScMo, especially for the large dimensions required if the mirror is positioned far from the entrance aperture, is presently unknown. Solutions to these challenges are proposed in [24]. As an example, a possible assembly of three ScMo pieces is shown in Fig. 7. The correspondingly HIPping (Hot Isostatic Pressing) required is scrutinised in, indicating that more R&D is required in the field too.

Another option which still has to be investigated thoroughly is the use of rhodium for M1, either as a thin layer with protective coating or as bulk material (a thick sheet of pure Rh). Rhodium was proposed in earlier times as a valid option since it exhibits sputtering rates which are intermediate between the light materials and the massive refractory metals like tungsten and molybdenum.
Fig. 9. Several optical designs: (a) retractable tube; (b) large M1; (c) recent design with updated position of antenna (half of the DFW-yellow and DSM-brownish both visible, DNB indicated as a red skeleton). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[25,26]. Whereas W and Mo have specular reflectivities in the order of 0.4–0.6, rhodium with expected values above 0.75 comes closer to the very best (e.g. aluminium at \( R_{sp} \geq 0.9 \)). Further studies are required in this respect since the lifetime of M1 is still a major design driver (see also [27]).

One of the most simple and universal mirror design solutions, compatible with the use of ScMo and Rh, is presented in Fig. 8. The optical mirror surface can be made either of ScMo or of rhodium (as bulk material or coating). A highly conductive leg constructed of Mo-alloy, cooled passively by holder via spacers, can provide
sufficient operational temperature and diminutive thermal distortion for the mirror.

3.4. The mirror chain

Several optical designs were studied in the frame of the German BMFF project (see Acknowledgement), such as those presented in Fig. 9. The arrangements (a) and (b), presented in [22] and [23] respectively, were dropped for practical reasons. The retractable tube, for instance, proves to be extremely hard to implement in view of the limited space behind the rear plate of the plug and the lack of possible coverage by remote handling. ITER and IC3 are now developing an actualised design, e.g. (c), which properly takes the current space reservations of the components to be integrated in the port plug into account.

With the first mirror under separate investigations and treatment, especially with respect to the materials used, several high-reflectivity candidates may be listed for the rest of the mirror chain, that is, for the secondary mirrors. The highest reflectivities are obtained in the considered visible wavelength range with dielectric mirrors (Fig. 10). Note that polarisation effects might be an issue. A report on tested mirrors can be found in [28]. A specular reflectivity of 98% can be achieved. Questions related to the lifetime, especially when exceeding 100–150 °C must still be clarified.

The next best candidate is aluminium, either the pure bulk material or coatings, the latter with or without protective layer. With this material, one would depart from the philosophy of getting close to an athermal design, mainly based on stainless steel in line with the DFW and DSM materials. The ultimate mirror selection will be determined by the robustness of the optical design and the positioning tolerances on single optical elements, especially the angular specifications.

4. Conclusions

The core CXRS diagnostic faces numerous design challenges on the following goals:

- providing the highest étendue and transmission for sensible detection limits,
- taking all possible measures to extend the lifetime of the first mirror, like an appropriate duct design, an efficient fast shutter and a cleaning device,
- complying with the ITER environment and ensuring a reasonable level of robustness against events which provoke misalignment.

The current design status is herewith documented before entering the final design phase of four years under an FPA with F4E. The choice of mirror materials and coating, if any, is still open since it may very much depend on the actual optical design.

Moreover, one can only stress the need for a comprehensive programme of prototyping (in some cases 1:1 components) and testing. A substantial engineering analysis must accompany these tests, particularly for the shutter, mirrors (including the holders) and, among others, a calibration scheme. The mandatory cleaning system may come in as a generic device.

In spite of the challenges, the preparatory work which is summarised in the present paper constitutes a good preparation to the final design home straight.

Acknowledgement

This work was supported by the German Federal Ministry of Education and Research (BMBF Grant no. 03FUS0007).

References


Fig. 10. Prototypes of dielectric mirrors (Ø 50–100 mm), multilayer coatings on stainless steel 1.4429 (closest to 316 LN).


