

CXRS-edge Diagnostic in the Harsh ITER Environment

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Abstract. CXRS diagnostics supply a set of important plasma parameters of fusion plasmas. According to the system requirements, the CXRS diagnostics in ITER should supply plasma velocity (poloidal and toroidal), impurity ion densities and ion temperatures. The ITER CXRS-edge diagnostic system must measure these parameters over the outer half of the plasma radius. The use of CXRS in ITER encounters serious challenges. In the paper the decisions made to overcome these difficulties for ITER CXRS-edge diagnostics system are described. Testing results of single-crystal Mo prototypes of first mirror are presented. The results of image quality modelling of optical scheme, where the in-vacuum optics uses only mirrors and all lenses are in the air part rather far from plasma, are presented. The results of laboratory test of the device developed for CXRS-edge on the base of transmission holographic gratings are presented.

1. Introduction

Charge exchange recombination spectroscopy (CXRS) diagnostics supply a set of important plasma parameters of fusion plasmas. According to the system requirements, the CXRS diagnostics in ITER should supply plasma velocity (poloidal and toroidal), impurity ion densities and ion temperatures. These parameters are important for plasma energy balance and plasma stability [1].

CXRS diagnostics are based on measurement of radiation of excited ions produced due to recombination of plasma ions by neutral hydrogen isotopes provided by either a heating or dedicated diagnostic neutral beam.

The ITER CXRS-edge diagnostic system must detect radiation spectra over the outer half of the plasma radius in several ranges of wavelengths and decompose the radiation lines shapes. The intensity of the lines determines the species density, the Doppler shift determines the velocity and the line width determines the temperature.

The use of CXRS in ITER harsh environment encounters serious challenges. In the paper the decisions made to overcome these difficulties for ITER CXRS-edge diagnostic system are described. These decisions may be useful for other optics diagnostic systems.

2. CXRS-edge Design

2.1. First Mirror

In order to collect enough light, the aperture of the collecting optics should be rather large. A large aperture, however, also leads to large heating from both plasma radiation and neutrons that can spoil mirror shape. Moreover, a large aperture results in substantial flow of plasma on first mirror with possible deposition on its surface.

Within the optical design the First Mirror (FM) is a critical element. The FM is closest to the plasma (see Fig.1) and gets to handle the highest heat loads, neutron loads and particularly particle fluxes. The positions of the FMs of the CXRS-edge system are in locations that are most likely to be 'deposition dominated', but given the complexity of the modeling and the

associated uncertainties, the possibility that the FM nonetheless would be in a ‘erosion dominated’ location cannot be ignored.

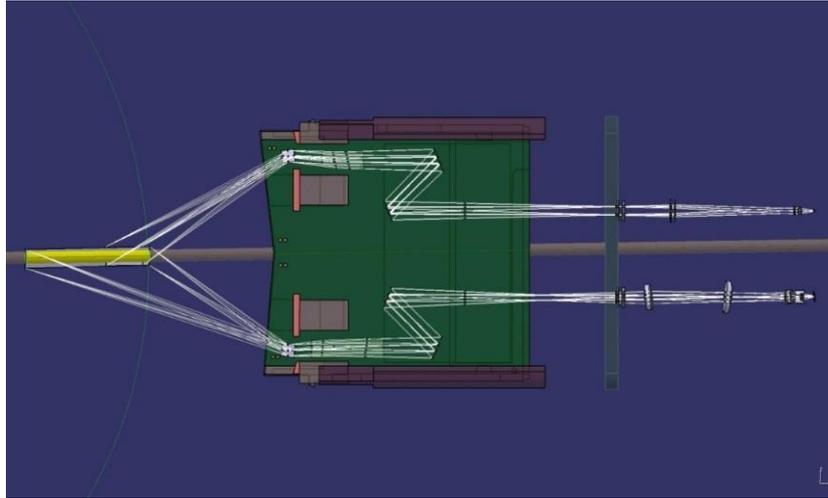


Fig. 1. Side view of light collecting systems (upper and lower) for CXRS-edge integrated in equatorial port #3.

Taking the above in mind single-crystalline molybdenum (SC Mo) is considered the best candidate material for the FM. It maintains its acceptable optical properties under erosion (or mirror cleaning that seems inevitable) and it can withstand the high thermal and neutron loads.

Two samples of first mirror made of SC Mo plate connected by either hot isostatic pressing (HIP) or brazing to a poly-crystalline Mo substrate with cooling channels were manufactured (see Fig.2) and tested for image quality under pressure and temperature of cooling water adequate to ITER conditions.

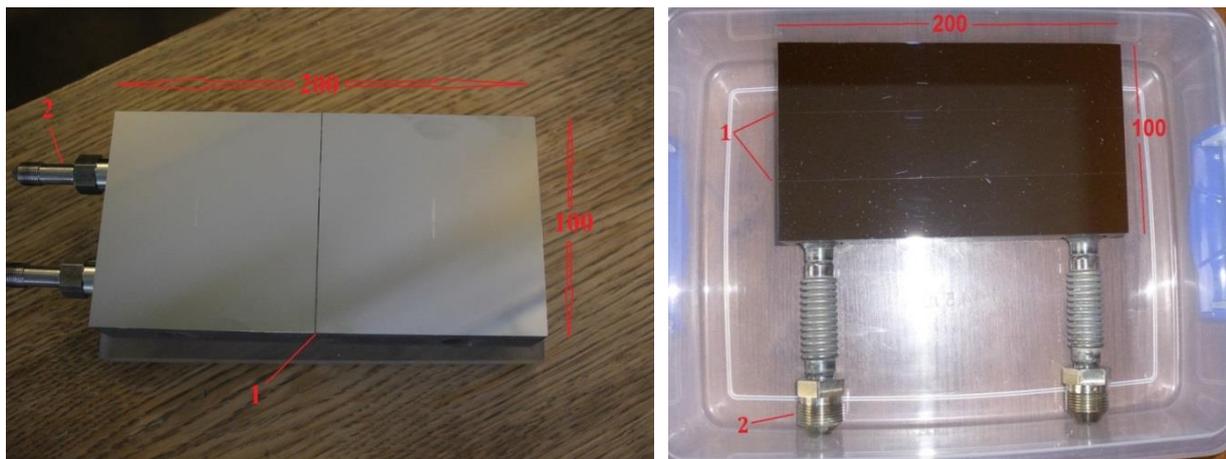


Fig. 2. FM made of two square plates (left), FM made of three stripes (right). (1) – gaps between single crystal Mo plates (4 mm thickness); (2) – water pipes.

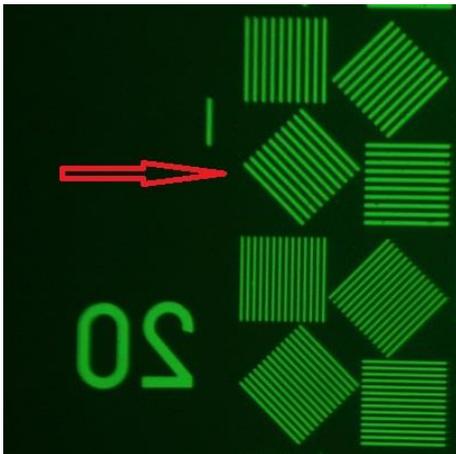
The facility for testing is shown on Fig.3. For testing, we used an image scale 1/1 and reference image with 15 grooves/mm, what corresponds to 0.067 mm spatial resolution in image plane. That corresponds to 1 mm spatial resolution inside plasma with scale 15/1, which will be used in ITER optical scheme, see below.

On Fig.4 one can see that the resolution of reference object image does not noticeably change when the water pressure and temperature are increased up to 165°C and 3.9 MPa. It does not

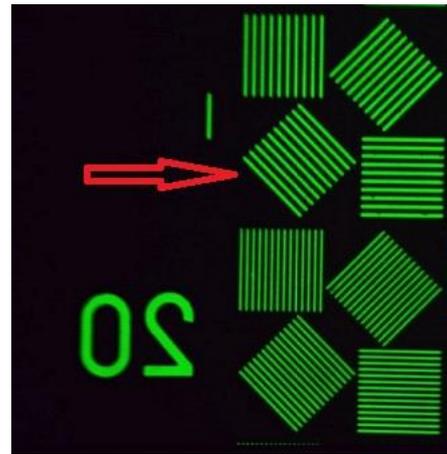
affect the image quality due to first mirror deformation. Also, no doubling of the image is observed, indicating that several reflecting SC Mo surfaces did not move relative to each other. Image is not even shifted.



Fig.3. Installation for FM mockups tests under water pressure and heating. (1) hydraulic and heating station; (2) vacuum vessel; (3) quartz window; (4) FM mockup; (5) water pipeline; (6) lenses; (7) test object; (8) "green" light filter; (9) camera holder.



Under the room conditions



Water temperature 165⁰C, pressure 3.9 MPa

Fig.4. Reference object image under test.

2.2. Optimization of Optical Scheme

The image quality of CXRS-edge optical system should be very good, because the needed spatial resolution is high, especially at the plasma boundary, to enable both detailed physics studies and control of advanced plasma scenarios (e.g. with Internal Transport Barriers).

However, the use of conventional glasses for lenses to meet the image quality is limited because of the degradation of their transparency with radiation fluence expected at ITER.

To mitigate the radiation influence on lens optics a scheme, where the in-vacuum optics uses only mirrors and all lenses are in the air part rather far from plasma, is developed. The results of image quality modelling are presented.

The main goal of optical scheme optimization was the size reduction of optical components aperture, while the their quantity was not changed. This reduction is very important for loads on FM and for its integration in port plug. In the optimized optical scheme for reduction of apertures the solid angle of light collection out of plasma was reduced by factor of 1,5. To keep the value of product of light collection solid angle by light source area, called etendue, $E=S \times \Omega$, the zoom factor of optics was increased from 10 to 15. As a result, the sight area in each spectral channel increased by 1,5 times without change of diameter of fibres, that transmit the light to spectral devices.

Eventually it was shown that it is possible to design the optical scheme with zoom factor 15, that correspond to ITER requirements for CXRS-edge system. But subsequent study with the use of ZEMAX showed that for the scheme with zoom factor 15 it is possible to move the lens module outside from vacuum volume. It is very important because the lifetime and maintenance of lenses and fibres are much improved in this case. Previously it was impossible because light beams could not pass through the vacuum window which size is limited by 160 mm. For optimized optical scheme with zoom factor 15 the footprints of light beams are shown on Fig.5 for lower viewing system.

From Fig.5 it is seen that all beams pass the vacuum window without cutting. Similar result was obtained for upper viewing system. Hence, for optical scheme with zoom factor 15 the optical schemes for upper and lower viewing systems with out-of-vacuum lens module were designed.

The space resolution in plasma that corresponds to the focal spots shown on Figs.6,7 reaches 14 mm for $r=a$ and 20 mm for $r=0,85a$. That means that designed optical scheme fully satisfies the specification of ITER for CXRS-edge.

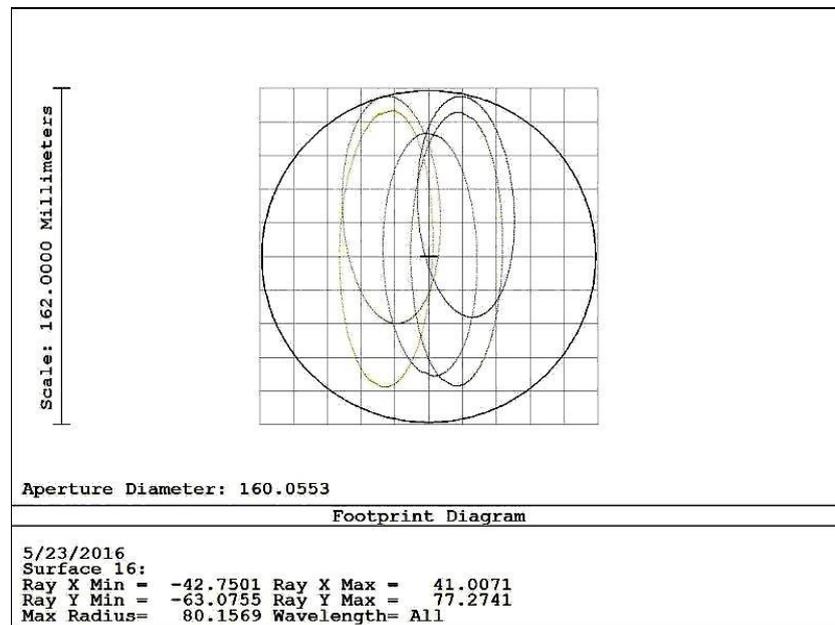


Fig.5. Footprints of light beams on vacuum window for optimized optical scheme with zoom factor 15.

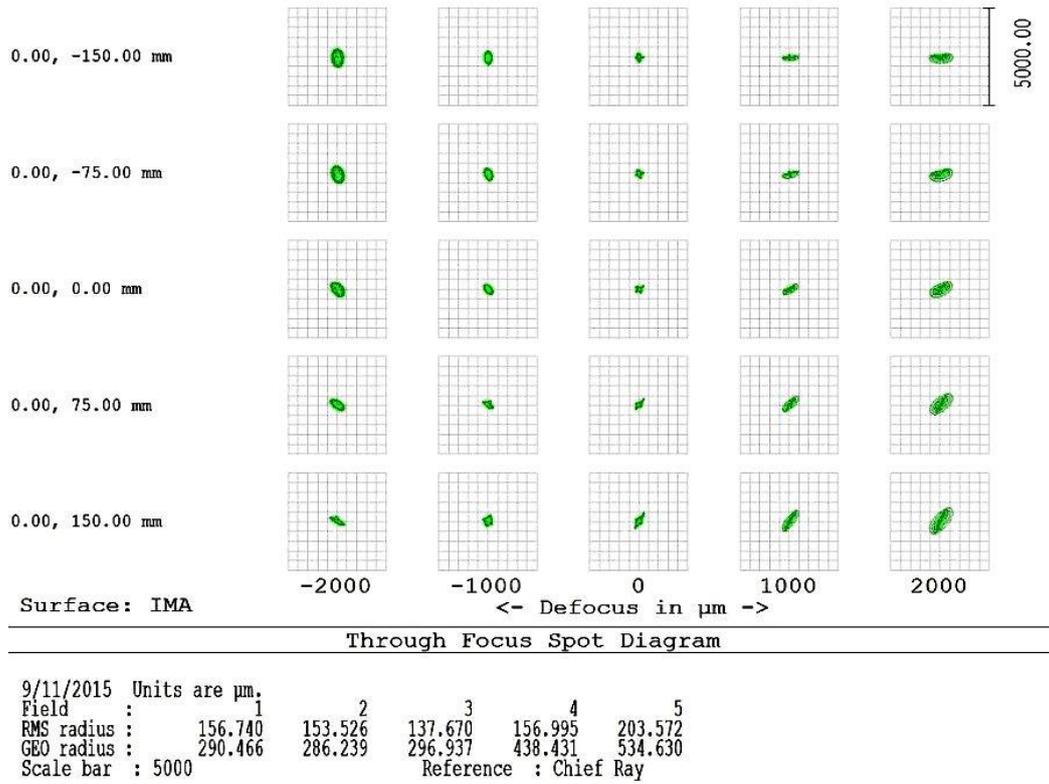


Fig.6. Focal spots for upper viewing system with out-of-vacuum lens module for wavelength $0.529 \mu\text{m}$.

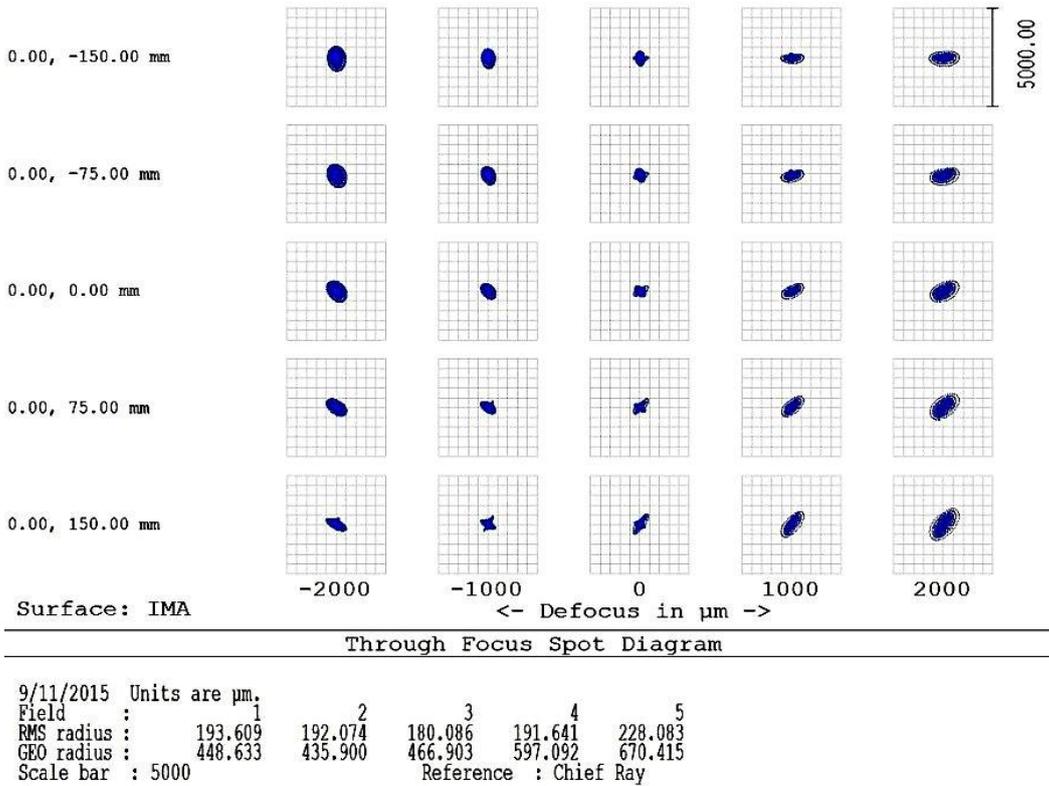


Fig.7. Focal spots for upper viewing system with out-of-vacuum lens module for wavelengths 0.466 and $0.656 \mu\text{m}$.

2.3. Density Measurements Calibration and Spectral Device

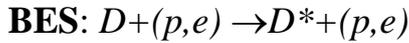
The harsh ITER environment limits access to the vacuum vessel for absolute intensity calibration to once every 4 or even 8 years. Given the loads on the first mirror described above, this is likely to be insufficient. Therefore, a novel technique was developed allowing calibrating the impurity density measurements by solely relying on a combination of the CXRS and Beam Emission (BES) measurement. This technique required the development of a multi-band spectrometer. Moreover, this spectrometer needed to have a high etendue (to collect enough light) and a high spectral resolution (for accurate measurements of the radiation lines widths and shifts).

The helium ash and low-Z impurity density can be retrieved from the measured intensities of the active CXRS lines and the BES emission. We show here as an example the CXRS reaction for an arbitrary impurity ion 'Z':



$$I_Z = 1/4\pi C_Z n_Z \int ds n_B(s) \langle \sigma v \rangle_Z$$

Here n_Z is the local impurity density, n_B is the local neutral beam density, $\langle \sigma v \rangle_Z$ is the effective atomic emission rate for CXRS emission and C_Z is the calibration factor.



$$I_{BES} = 1/4\pi C_{BES} n_e \int ds n_B(s) \langle \sigma v \rangle_{BES}$$

Here n_e is the local electron density, $\langle \sigma v \rangle_{BES}$ is the effective atomic emission rate for beam emission and C_{BES} is the calibration factor. The line integral in both cases refers to the intersection of neutral beam path and line of sight.

Different viewing geometries for CXRS and BES would require modeling the local neutral beam density over the whole plasma based on the beam stopping processes; that is ionization by electrons and ions and by charge exchange losses and verifying the modelling results with the I_{BES} measurements. This would require accurate absolute calibrations of the BES system and precise beam and line of sight geometry data.

However, combining BES and CXRS if the same viewing chords are used cancels out the line integration. In this case two absolute calibrations (for CXRS and BES system) are replaced by a single relative cross-calibration between the CXRS and the BES system:

$$\frac{n_Z}{n_e} = \left(\frac{C_{BES}}{C_Z} \right) \frac{I_Z \langle \sigma v \rangle_{BES}}{I_{BES} \langle \sigma v \rangle_Z}$$

For this simplification the complete light collection geometry for CXRS and BES needs to be identical. This includes the same collection volume and solid angle. In practice it means that the CXRS and BES systems need to be as identical as possible for as long as possible. For instance, a single spectrometer with 3 wavelength channels (2 for CXRS and 1 for BES) is preferred [2].

The devices suitable for the CXRS-edge diagnostic should combine features of both polychromators and high resolution spectrometers in separate spectral ranges (multi-band). Such a device based on transmission holographic gratings was developed. It has high etendue, excellent spectral resolution, and reasonable size. The design of device ensures the same optical

path for both CXRS and BES diagnostics what favors the calibration. The scheme and the picture of high etendue spectrometer (HES) are shown on Figs.8 and 9, respectively.

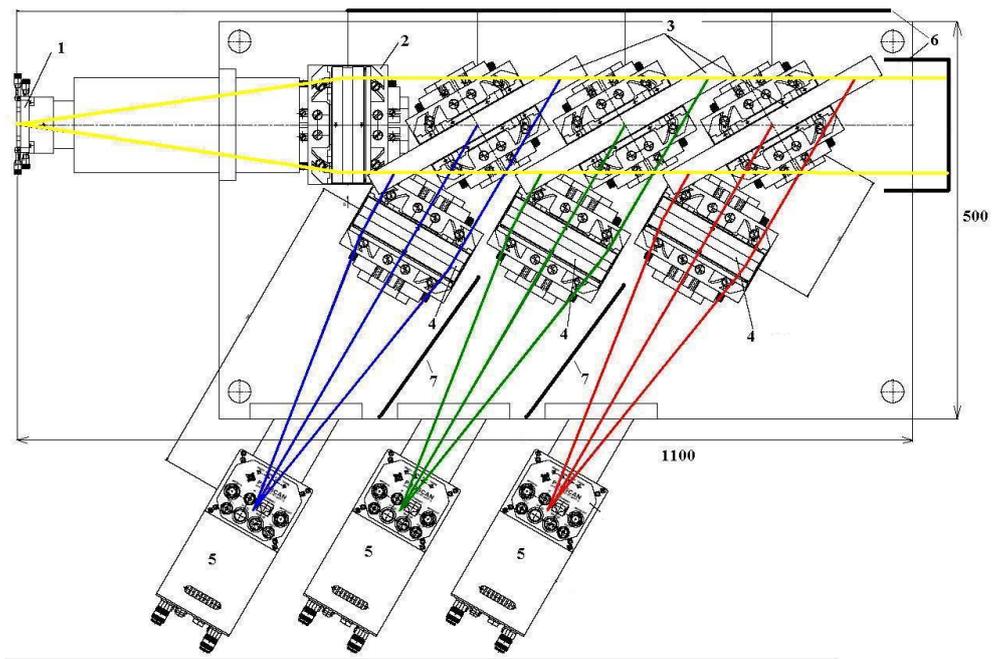


Fig.8.Principle scheme of the multi-channel HES spectrometer. (1) entrance slit; (2) collimator objective lens; (3) holographic transmission gratings for 468 ± 5 nm, 529 ± 5 nm and 656 ± 6 nm spectral ranges; (4) camera objective lenses; (5) CCD cameras; (6) light traps/viewing dumps; (7) light shields/baffles.

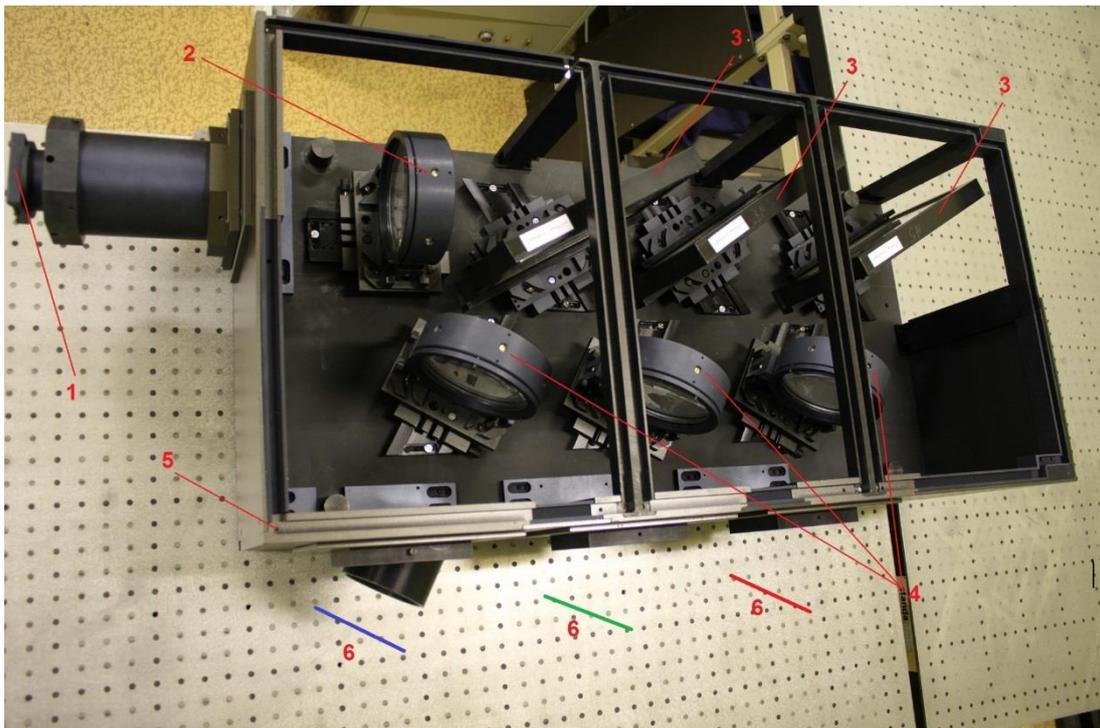


Fig.9. Picture of multi-channel HES spectrometer. (1) entrance slit; (2) collimator objective lens; (3) holographic transmission gratings; (4) camera objective lenses; (5) enclosure; (6) image planes.

Laboratory tests confirmed that the spectrometer meets the requirements. The technical properties of HES spectrometer obtained during the laboratory tests are listed below.

- Working spectral ranges: 468 ± 5 nm, 529 ± 5 nm and 656 ± 6 nm;
- 40 – 50% grating efficiency for the working spectral ranges;
- F-number = 3;
- Linear dispersion: $3.4 - 5 \text{ \AA}^0/\text{mm}$;
- Stigmatic image (astigmatism value: $0.025 - 0.03$ mm);
- Magnification (in horizontal and vertical direction) = 1;
- Entrance slit height: up to 25 mm;
- Image plane size: 25 x 25 mm;
- Max. spectral resolution $\sim 0.2 \text{ \AA}^0$;
- HES spectrometer contrast: $K \gg 60\,000$.

These laboratory tests were done without the light traps/viewing dumps or shields/baffles, which are shown in Fig.8. Light traps and shields will be installed for future spectrometer improvement. Also, we plan to install interference filters before the image plane in each spectral channel. This will reduce the stray light level in each spectral channel and helps to avoid other negative effects.

One more future step is the improvement of the diffraction and transmission efficiency of the holographic gratings. It is expected that the diffraction efficiency could be increased up to 50% and the transmission efficiency up to 85–95%.

3. Conclusions

Flat first mirror could be produced from few SC Mo pieces. Such FM could give high quality image in the wide range of temperature and water pressure: from 15 up to $165 \text{ }^\circ\text{C}$ and from atmosphere up to 3.9 MPa, correspondingly.

The optical scheme optimization resulted in diminishing of FM aperture by two times and gave the opportunity to have the in-vacuum optics that uses only mirrors and all lenses are in the air part rather far from plasma. This improves the lifetime, integration and maintenance of the system.

The HES spectrometer designed for CXRS-edge has very good optical characteristics and permits both CXRS and BES measurements, what favors the calibration of CXRS.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organisation.

References

- [1] TUGARINOV S.N., et al., “Development of the concept of charge-exchange recombination spectroscopy for ITER”, Plasma Physics Reports, vol. 30, No 2, 2004, pp.128-135.
- [2] TUGARINOV S.N., et al., “The tri-band high-resolution spectrometer for the ITER CXRS diagnostic system”, ISSN 0020-4412, Instruments and Experimental Techniques, vol. 59, No 1, 2016, pp.104–109.