Technical Specification

Soft X-ray spectrometer

1. Introduction

The specified item is a soft X-ray spectrometer and its accessories / components, hereinafter abbreviated as SXR spectrometer. For purposes of this Technical Specification, the SXR spectrometer is defined as a standalone measuring instrument connected to a diagnostic port interface of the COMPASS-U tokamak. Each requirement, which must be fulfilled, is introduced by the phrase "**Requirement:**" and indicated by a **bold font**. Related circumstances are also provided to put the requirement into context (not using a bold font).

Requirement No. 1.1: It is strictly prescribed to meet all the specified requirements, listed in this Technical Specification, at the same time, unless explicitly stated otherwise.

2. General description

The SXR spectrometer for measuring electromagnetic radiation in the spectral range of about 2 - 9 keV (0.62 nm - 0.14 nm) is aimed at monitoring of highly ionized (mainly high-Z metallic) impurities in the core of high-temperature plasmas at the COMPASS-U tokamak with core plasma temperatures $T_e \sim 1$ - 5 keV and core electron densities $n_e \sim 1 - 3*10^{20}$ m^{-3}. See more details about COMPASS-U in [1]-[4].

These impurities either originate in the plasma-facing components (mainly tungsten and nickel-chromium-based alloy components as nickel, chromium, molybdenum, iron) or will be artificially introduced for physics studies (e.g. argon). The SXR spectrometer should allow a) monitoring of all these elements by resolving well their characteristic spectral lines in spectral regions of interest (ROIs) specified in the further paragraphs, and b) measuring parameters of these observed lines such as intensity, line width and spectral shift.

The vacuum volumes of the tokamak vacuum vessel and of the spectrometer will be coupled, therefore, mutual vacuum compatibility is required and described in detail.

The spectrometer will be operated during high-temperature plasma discharges of COMPASS-U and exposed to a harsh environment around the tokamak (stray magnetic field, gamma and neutron radiation), see [1]-[4]. The maximum magnitudes and fluxes in the tokamak hall of COMPASS-U are provided to give an overview of the worst possible conditions around the spectrometer, however, the shielding itself is not the subject of this tender.

The spectrometer is planned to be located in the tokamak hall (default) in early operational phases of COMPASS-U, when low neutron and gamma radiation fluxes are expected. In the

tokamak hall, the spectrometer will be mounted on a tilting table at a height of 3 m above the floor. In later operational phases with the full performance of the tokamak, when high radiation fluxes can appear, the spectrometer will be moved further from the tokamak hall to a shielded diagnostic room. Spatial and other conditions and constraints for both the locations are introduced and must be reflected.

[1] [redacted] Fusion Eng. Des. 123 (2017) 11;
https://doi.org/10.1016/j.fusengdes.2017.03.002

[2] [redacted] Fusion Eng. Des. 169 (2021) 112490;
https://doi.org/10.1016/j.fusengdes.2021.112490

[3] [redacted] Fusion Eng. Des. 146 (2019) 1703;
https://doi.org/10.1016/j.fusengdes.2019.03.020

[4] [redacted] et al., Fusion Eng. Des. 191 (2023) 113545;
https://doi.org/10.1016/j.fusengdes.2023.113545

3. Detailed description of the SXR spectrometer

Requirement No. 3.1: The SXR spectrometer must be based on soft X-ray diffraction on (Bragg) crystals. The prescribed type is the Johan mount with both the crystal and the detector located on its Rowland circle. The observed tokamak plasma will be located at greater distances, described further.

Requirement No. 3.2: Full remote control (remote handling) of the SXR spectrometer and all its controllable / steerable parts. For example, it includes remote control of pumping, opening and closing of the gate valve, adjusting the position of (Bragg) crystals, setting of the detector and the data acquisition. It is motivated by a partially restricted access to the tokamak hall between experiments (no access during measurements; partial access between several hours-long shifts).

Requirement No. 3.3: The component of the spectrometer, which will be connected to a diagnostic port extension of the tokamak vacuum vessel, is the gate valve. The gate valve must be equipped with the DN 100 CF (knife-edged flange according to ISO 3669:2020) interface and its opening must allow the tokamak plasma to be observed. The gate valve will be connected to a DN 100 CF (knife-edged flange according to ISO 3669:2020) flange on the tokamak side.

Requirement No. 3.4: Radiation with energies lower than 10 keV (mainly visible light and UV) that has not passed through the open gate valve of the SXR spectrometer must be shielded and must not be measured by the detector of the SXR spectrometer.

Note that the tokamak hall cannot be considered a dark room and radiation can come from various directions.

3.1. Main components of the SXR spectrometer

A simplified scheme (indicative) of the SXR spectrometer is provided in Figure 1, where a possible configuration showing its main components is indicated.

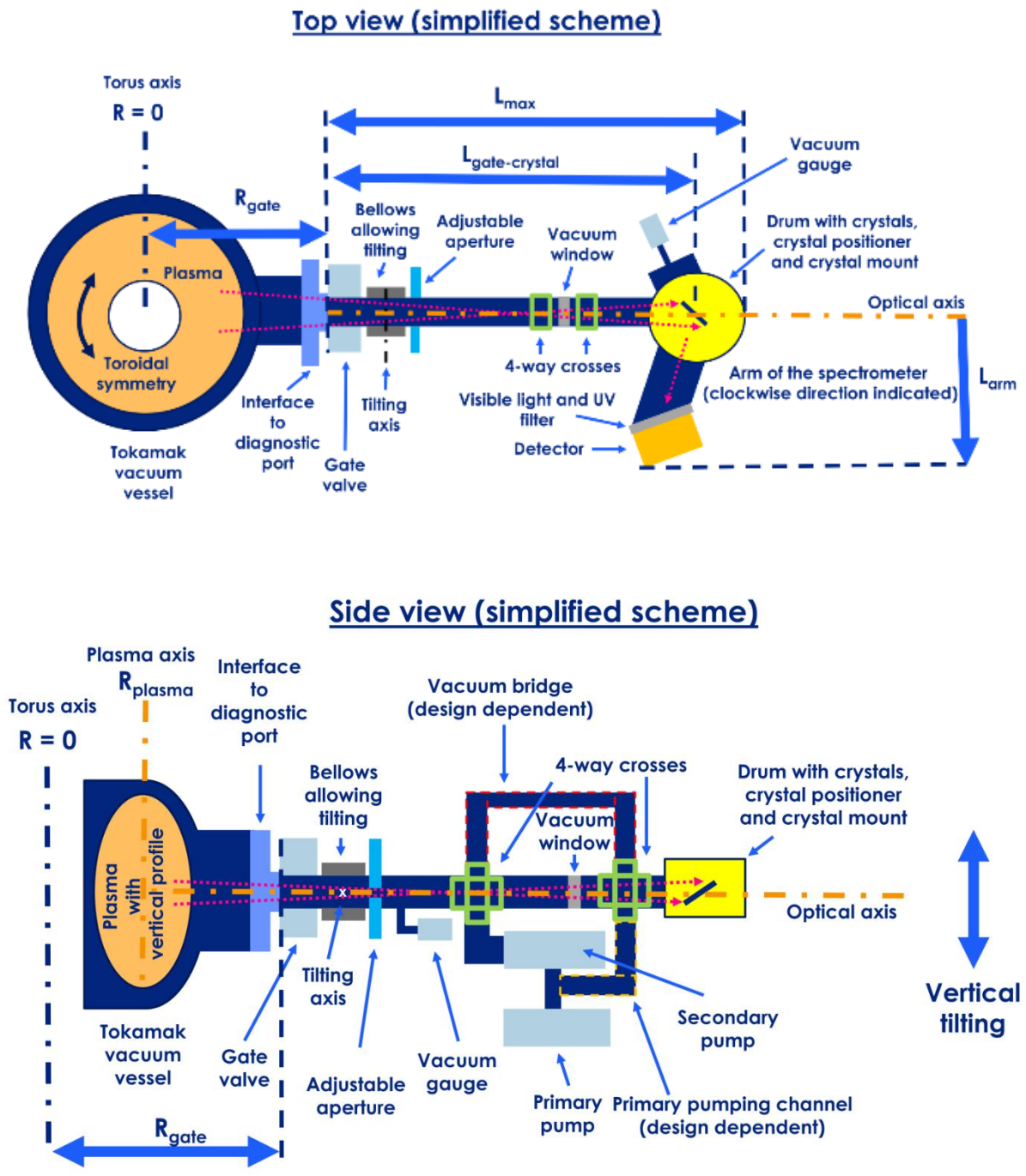

Figure 1: Simplified scheme of the SXR spectrometer: a) top view, b) side view

In Figure 1, the named distances and angles are

a) measured against the vertical torus axis (at R=0):
   R_{plasma} = 0.894 m is the distance to the plasma center, also called major radius;
   R_{gate} = 2.5 m is the distance to the (closer) edge of the gate valve.
b) measured against the edge of the gate valve closer to the tokamak (at R_{gate}):
   $L_{gate\text{-}crystal}$ is the distance (along the optical axis) to the crystal center;
   L_{max} is the distance (along the optical axis) to the most distant point of the drum (with crystals, crystal positioner and crystal mount).
c) measured against the optical axis of the SXR spectrometer:
   L_{arm} is the distance (in the horizontal plane) to the most distant point of the arm of the SXR spectrometer;
   Vertical tilting is the angle of the SXR spectrometer tilting.

<u>Requirement No. 3.1.1:</u> It is prescribed to set $L_{gate\text{-}crystal}$ = 2.5 m (it only applies to the location of the SXR spectrometer in the tokamak hall). The Seller can change this distance by ± 0.25 m, if necessary for technical reasons.

Note that the distance between the crystal and the plasma core (object of measurement) is R_{gate}+ $L_{gate\text{-}crystal}$- R_{plasma}, i.e. about 4.1 m for $L_{gate\text{-}crystal}$ = 2.5 m.

<u>Requirement No. 3.1.2:</u> L_{max} < 3.25 m; it only applies to the location of the SXR spectrometer in the tokamak hall.

<u>Requirement No. 3.1.3:</u> L_{arm} < 1 m; if this distance is proposed to be larger by the Seller, the proposed design must be negotiated well in advance with the Buyer and, if accepted by the Buyer, it must be confirmed by a written agreement (e-mail from the Buyer is acceptable).

<u>Requirement No. 3.1.4:</u> The arm of the SXR spectrometer must be placed in a horizontal plane. The SXR spectrometer must allow both orientations of the spectrometer arm, clockwise (default – also for delivery; indicated in Figure 1) and counter-clockwise. Changing the arm orientation will be done manually. The Seller must provide written instructions how to make this adjustment.

<u>Requirement No. 3.1.5:</u> With the exception of the arm of the SXR spectrometer and parts directly attached to it, all other parts of the SXR spectrometer must be located closer than 0.5 m from its optical axis in the horizontal plane; if this distance is proposed to be larger by the Seller, it must be negotiated well in advance with the Buyer and confirmed by a written agreement (e-mail from the Buyer is acceptable).

The distance of about ± 0.5 m corresponds to the horizontal dimension of the reserved section at the location of the gate valve, i.e. at R_{gate} = 2.5 m.

<u>Requirement No. 3.1.6:</u> The used bellows must allow vertical tilting of the SXR spectrometer, having the tilting axis in the middle of the bellows, by up to ± 10° (up and down). The SXR spectrometer must allow its full operation for any inclination within this range.

In the tokamak hall, the spectrometer will be mounted on a tilting table. The table, standing on the floor, will be designed by the Buyer with respect to the Design Review of the SXR

spectrometer, delivered by the Seller. The table will hold the optical axis of the SXR spectrometer at the tokamak midplane, i.e. about 2.85 m above the floor.

<u>Requirement No. 3.1.7:</u> The spectrometer must, at least, contain these physical components:

1) **Gate valve**, separating the tokamak from the SXR spectrometer
2) **Bellows,** allowing vertical tilting of the SXR spectrometer
3) **Adjustable aperture**, limiting the vertical view of the spectrometer
4) **Complete vacuum duct of the spectrometer**, ensuring a vacuum environment in all parts of the spectrometer, where it is needed
5) **Vacuum window,** allowing transmission of detected soft X-ray radiation from the tokamak, and separating an ultra-high vacuum part of the SXR spectrometer, connected to the tokamak, from the rest of the SXR spectrometer
6) **2 pieces of the 4-way cross**, located one from each side of the vacuum window to allow pumping of both parts of the SXR spectrometer and future easy realization of the vacuum bridge
7) **(Bragg) Crystals positioner and crystal mount**, allowing positioning of each (Bragg) crystal to the measuring configuration
8) **Primary pump**, reaching a fore vacuum level in the SXR spectrometer allowing further pumping by the secondary pump
9) **Secondary pump**, allowing pumping of the SXR spectrometer down to an ultra-high vacuum level
10) **2 pieces of full-range vacuum gauges**, measuring the pressure in both vacuum parts of the spectrometer
11) **Universal control unit** for the vacuum gauges and the secondary pump, **or control units** for each vacuum gauge and for the secondary pump
12) **Spectral filter for visible light and UV radiation,** if not already sufficiently filtered by the vacuum window, maximizing a signal-to-noise ratio of the soft X-ray detector
13) **Set of (Bragg) crystals**, providing soft X-ray diffraction in the SXR spectrometer, their constructive interference and partial imaging for the selected wavelengths on the soft X-ray detector plane
14) **2D soft X-ray detector**, allowing detection of soft X-ray radiation from the tokamak resolved in wavelength, in space and in time

Requirements for each mentioned component, which must be fulfilled, are set separately in the next paragraphs.

Some parts of the SXR spectrometer named in Figure 1 are part of the more complex physical components listed above. This is the case of the drum (with crystals, crystal positioner and crystal mount), the arm of the spectrometer, the primary pumping channel and the vacuum bridge, encapsulated in the component called Complete vacuum duct of the spectrometer. These parts will be further mentioned.

3.2. Spectral range of the SXR spectrometer

<u>Requirement No. 3.2.1:</u> The minimum set of the spectral regions of interest (ROI) that must be covered by the SXR spectrometer is specified in Table 1. Each spectral ROI must be covered at once, i.e. the entire ROI must be recorded by the detector in a single exposure. All specified ROIs must be covered by the crystals stored within the drum (with crystals, crystal positioner and crystal mount) of the spectrometer. These crystals must be exchangeable for further measurements in another of the specified ROIs remotely and without venting the spectrometer or personal access to it.

It is expected that all the specified ROIs will be covered by 3-5 crystals.

Table 1: The minimum set of the spectral ROIs (specified by wavelengths) that must be covered by the SXR spectrometer. These ROIs correspond to metallic elements of the plasma-facing components (W, Ni, Cr, Mo, Fe) and Ar for physics studies. The third column (grey) of the table is only informative.

ROI number	**Minimum required spectral ROI to be covered**	Element/ionisation state and the expected wavelength
1	**0.3945-0.4000 nm**	$W^{43+ - 44+}$ (0.3960 - 03995 nm) Mo^{37+} (0.3955 - 0.3995 nm) Ar^{16+} (0.3950 - 0.3995 nm)
2	**0.3715-0.3800 nm**	$W^{43+ - 47+}$ (0.3720 - 0.3795 nm) $Mo^{31+ - 32+}$ (0.3740 - 0.3785 nm) Ar^{17+} (0.3730 - 0.3735 nm)
3	**0.5190 - 0.5240 nm**	$W^{45+ - 46+}$ (0.5195 - 0.5235 nm) Mo^{32+} (0.5200 - 0.5215 nm)
5	**0.4635 - 0.4685 nm**	$W^{38+ - 39+}$ (0.465 - 0.482 nm)
6	**0.4685 - 0.4715 nm**	
7	**0.4800 - 0.4830 nm**	
8	**0.1845 - 0.1875 nm**	Fe^{24+} (0.185 - 0.187 nm)
9	**0.1770 - 0.1790 nm**	Fe^{25+} (0.1775 - 0.1785 nm)
10	**0.2085 - 0.2100 nm**	Cr^{23+} (0.2090 - 0.2096 nm)
11	**0.1525 - 0.1540 nm**	Ni^{27+} (0.1530 - 0.1535 nm)

3.3. Spectral resolution of the SXR spectrometer

<u>Requirement No. 3.3.1:</u> The minimum spectral resolution $\Delta\lambda$ at the wavelength λ that the SXR spectrometer must achieve is $\lambda/\Delta\lambda = 2500$. For the ROI number 1 and 2, the minimum prescribed spectral resolution is set to $\lambda/\Delta\lambda > 3000$.

Such minimum spectral resolution should be high enough to distinguish close tungsten or other metal lines (identification and measurement of line intensity). For the ROI number 1 and 2, where argon lines are located and their line width measurements are expected, the spectral resolution should be maximized.

3.4. Detector of the SXR spectrometer

<u>Requirement No. 3.4.1:</u> The sensor of the detector must be highly sensitive for soft X-ray radiation measured by the soft X-ray spectrometer. Its minimum quantum efficiency QE must be QE > 60% for the ROI number 1 - 7, and QE > 15 % for the ROI number 8 - 11.

The higher sensitivity in the spectral region covered by the SXR spectrometer, the better. Detector sensitivity to neutrons and outside the spectral region covered by the SXR spectrometer is not desirable.

<u>Requirement No. 3.4.2:</u> The sensor must be a two-dimensional array of measuring points and be able to collect data with any above-mentioned spectral ROI at spectral resolution of the SXR spectrometer.

The sensor axis representing spectral resolution is expected to have several hundred up to thousands of measured points. The spatial coordinate should be covered by at least one measured point at the best time resolution, or by tens or more measured points at a worse time resolution.

<u>Requirement No. 3.4.3:</u> For the ROI number 1 and 2, any argon line peak, corresponding to the plasma with ion temperature $T_i > 1$ keV, must be sampled with at least 5 pixels (of the detector spectral axis) above 10 % of the peak intensity.

<u>Requirement No. 3.4.4:</u> Time resolution of the measurement (frame rate) must be better (shorter) than 40 ms. The maximum duration of the measurement is lower than 15 s and must be covered with this (best) time resolution continuously.

The higher time resolution (down to hundreds of microseconds), the better.

First simulations of tungsten spectral lines near 0.4 nm indicate that for typical discharge conditions the radiated power of a line with full width at half maximum about $2*10^{-4}$ nm will be of order of 10^{-5} - 10^{-4} W per circular area of 10 cm in diameter at the 4.1 m distance from the plasma (expected crystal position), if the observation is done through a cylinder of 10 cm in diameter. As this number is very imprecise and will also be heavily influenced by many factors of the discharge, it should be taken only as a very rough order estimate.

<u>Requirement No. 3.4.5:</u> An external trigger input must be available.

The SXR spectrometer will be a part of the COMPASS-U diagnostics system and must be synchronized with the other COMPASS-U systems. This requires a trigger input that will start the measurement. The first exposure should start within 10 μs after trigger event. Additionally, an external clock input that will define SXR spectrometer time base is desirable. The external clock input will have constant frequency square or sinusoidal waveform for all possible frame rates and exposure durations.

Requirement No. 3.4.6: The sensor is prescribed to be located in vacuum at pressures lower than 100 Pa.

The pressure level depends on the vacuum scheme of the SXR spectrometer and can be as low as 10^{-6} Pa.

Requirement No. 3.4.7: If the sensor is sensitive for visible light or UV radiation, both these spectral regions must be well rejected, e.g. by the vacuum window in the vacuum duct of the SXR spectrometer, or by using a dedicated spectral filter in front of the detector. A high transmittance for soft X-ray radiation (> 40% over the entire measured spectral range) of such filter / window must be ensured.

Parameters of the sensor are mainly dictated by the required spectral and time resolutions.

Requirement No. 3.4.8: High vacuum (down to 10^{-5} Pa) compatibility of the detector.

Soft X-ray radiation is highly attenuated in the air at atmospheric pressure. Therefore, measurement in vacuum is desirable. On the other hand, the use of a vacuum window between the tokamak and the SXR spectrometer to separate these systems, i.e. to increase safety, again comes with attenuation issues. High vacuum compatibility of the detector is required to keep flexibility of the SXR spectrometer design for future modifications. However, the detector can be fully located in the vacuum duct of the SXR spectrometer or to have an in-vacuum sensor only and a vacuum interface with the electronics placed on the atmospheric side.

Requirement No. 3.4.9: A fully featured and well documented Application Programming Interface (API) must be provided for both detector setup and data acquisition.

Requirement No. 3.4.10: A free space of at least 3 cm around the sensitive parts of the detector for the future installation of stray magnetic field shielding must be kept. The corresponding attachment points for this metallic (mu-metal and/or magnetically soft iron) shielding must be specified by the Seller no later than the Design Review.

3.5. Materials

In a tokamak, strong magnetic fields are generated that can induce forces in nearby magnetic materials. Additionally, the non-negligible amount of magnetic material near the tokamak can affect / disturb the plasma inside.

Requirement No. 3.5.1: M**aterial selection - stainless steel AISI 304L (or AISI 316L) is assumed for the main vacuum parts of the SXR spectrometer. Non-magnetic materials (materials with magnetic permeability close to unity or with susceptibility close to zero) are highly preferred to be used in all parts of the spectrometer.**

Requirement No. 3.5.2: Any proposed use of beryllium or other dangerous materials in the SXR spectrometer must be first proposed to the Buyer and such use is permitted only after confirmation by the Buyer by a written agreement (e-mail from the Buyer is acceptable).

Requirement No. 3.5.3: The use of beryllium as a vacuum window at a non-zero pressure difference ($\Delta p > 10^{-4}$ Pa) is prohibited.

Although beryllium vacuum windows are visible light and UV radiation tight, the possible sucking of beryllium into the tokamak vacuum vessel represents a serious safety concern and must be avoided.

3.6. Electrical and electronic interfaces

The tokamak hall will allow only limited personal access (also to the spectrometer) – most likely no access between tokamak shots, limited access between shifts (daily basis), full access during shutdowns (several months basis). Therefore, remote control systems are a must.

In the tokamak hall, electric potential differences (voltage) at longer distances can appear. Also, hard radiation (neutrons and gammas) is expected in the tokamak hall. Therefore, the number of electrical connections from the tokamak hall and physical holes in the concrete around hall should be minimized. Also, complex electronics systems are not recommended to be placed there. Therefore, USB interfaces, having a short distance limit and representing an electrical connection, are not preferred as the type of interface used.

Requirement No. 3.6.1: All electrical systems of the spectrometer, located in the tokamak hall, must allow remote control / remote handling.

Requirement No. 3.6.2: Prescribed interface type - ethernet (via optical fibers using duplex LC connectors is preferred over twisted cables using an RJ-45 connector). Direct electrical outputs are allowed only for simple systems but must be negotiated with the Buyer and confirmed by a written agreement (e-mail from the Buyer is acceptable).

These signals (direct electrical outputs) will be, most probably, converted to ethernet in the tokamak hall and included in the Control, Data Access and Communication (CODAC) system of the COMPASS-U tokamak.

If some components are equipped only with a USB interface, USB-to-optical/ethernet converters must be added to meet the above-mentioned requirement. However, the use of these components should be minimized.

Requirement No. 3.6.3: A full-featured and well documented Application Programming Interface (API) in English must be provided for all more complex systems (as a control and acquisition API for the detector of the SXR spectrometer or a control API for the motorized stages for proper positioning of the crystal or the detector).

Requirement No. 3.6.4: The SXR spectrometer must be fully operable and capable of setup, measurement, data acquisition, calibration, complete status reporting and self-test just using the API. The API must provide parameters checks so that parameter settings

outside ranges or operable limits are rejected. If use of the API requires a license, this license for at least 10 years must be a part of the delivery.

3.7. Vacuum compatibility and vacuum systems

The COMPASS-U tokamak will use ultra-high vacuum (UHV) technology to achieve high-temperature discharges in very pure hydrogen, deuterium or helium (pre-discharge pressure ~ 10^{-6} Pa; pressure after deuterium gas puff and during discharges ~ 10^{-1} – 10^{0} Pa; pressure during Glow Discharge Cleaning usually done in helium < 10 Pa). COMPASS-U is planned to be a carbon-free device, therefore, use of any materials potentially contaminating the tokamak vacuum vessel by carbon should be minimized and only oil-free pumping systems are allowed.

The proposed location of all vacuum systems is schematically indicated in Figure 1; however, it can be modified by the Seller. The indicated arrangement is motivated by minimizing the effect of the stray magnetic field on the vacuum systems, by minimizing required space perpendicular to the optical axis in the horizontal plane while maintaining the possibility of vertical tilting of the SXR spectrometer.

Requirement No. 3.7.1: Vacuum technology prescribed for use in the vacuum parts of the SXR spectrometer that will be directly connected to the vacuum volume of the tokamak vacuum vessel (i.e. from the gate valve of the SXR spectrometer to its vacuum window): compatible with ultra-high vacuum (UHV) conditions and with a hydrogen environment (in the tokamak vacuum vessel) down to 10^{-6} Pa, according to Article 2.4 of the attached document "COMPASS-U Vacuum Requirements". The use of knife-edged flanges according to ISO 3669:2020 and oxygen-free high thermal conductivity (OFHC) copper gaskets is required.

Requirement No. 3.7.2: Vacuum technology prescribed for use in the vacuum parts of the spectrometer behind the vacuum window (not being directly connected to the vacuum volume of the tokamak vacuum vessel): at least high vacuum compatible with pressures down to 10^{-5} Pa (UHV compatibility is preferred), according to Article 2.4 of the attached document "COMPASS-U Vacuum Requirements".

The use of knife-edged flanges according to ISO 3669:2020 and oxygen-free high thermal conductivity (OFHC) copper gaskets is strongly preferred also in the vacuum parts of the spectrometer behind the vacuum window (not being directly connected to the vacuum volume of the tokamak vacuum vessel).

Requirement No. 3.7.3: The pumping system of the SXR spectrometer must ensure UHV conditions near the gate valve. Opening into the tokamak vessel will be only possible for pressures at the level of 10^{-6} Pa.

Baking of the vacuum duct of the SXR spectrometer is expected; the Seller should propose its acceptable level relevant to the SXR spectrometer design.

Requirement No. 3.7.4: Vibrations from the pumping system toward the spectrometer as well as toward the tokamak should be minimized.

<u>Requirement No. 3.7.5:</u> The pumping system must contain the primary pump and the secondary pump. The primary pump must be a dry primary pump of the scroll type with the pumping speed higher than 10 m^3/h and the ultimate vacuum level at least 10 Pa. The primary pump must have a prescribed service interval longer or equal to 8000 hours and powered by 240 V AC (single phase grid). The secondary pump must be a turbomolecular pump (TMP) with mechanical or hybrid bearings (NOT ONLY magnetically levitated rotor), DN 100 CF (knife-edged flange according to ISO 3669:2020) vacuum connection, pumping speed higher than 200 l/s (H_2 at < 10^{-1} Pa), ultimate pressure < 10^{-7} Pa, air-cooled, and with arbitrary mounting orientation.

<u>Requirement No. 3.7.6:</u> Horizontal mounting orientation along the optical axis (directed away from the tokamak) is required for the turbomolecular pump due to (mainly vertical) stray magnetic field around the tokamak.

To minimize the size of the tilting table, it is assumed to place the turbomolecular pump under the main vacuum duct of the SXR spectrometer.

<u>Requirement No. 3.7.7:</u> A free space of at least 3 cm around the secondary pump for the future installation of stray magnetic field shielding must be kept. The corresponding attachment points for this metallic (mu-metal and/or magnetically soft iron) shielding must be specified by the Seller no later than the Design Review.

<u>Requirement No. 3.7.8:</u> The gate valve ensuring connection / disconnection of the SXR spectrometer and the interface to the tokamak diagnostic port must be a remotely driven ultra-high vacuum pneumatic gate valve with DN 100 CF (knife-edged flange according to ISO 3669:2020), bakeable up to 150 °C, with passive safety: positive lock-over center mechanism and made of non-magnetic material. The gate valve must be vacuum tight (leak tightness ≤ $2*10^{-10}$ $Pa.m^3/s$) at the pressure difference of $\Delta p \leq 10^5$ Pa.

Opening and closing of the valve using microcontrollers / PLCs, driven by EPICS, is expected after integration to the CODAC system of the tokamak.

<u>Requirement No. 3.7.9:</u> Two full-range vacuum gauges (for pressure range of 10^{-6} - 10^5 Pa) will monitor the pressure in the spectrometer. One gauge must be placed between the gate valve and the vacuum window of the SXR spectrometer to detect the possible pressure difference against the vacuum vessel of the tokamak. The second gauge must monitor the pressure in the spectrometer behind the vacuum window (in the drum with the crystals and in the spectrometer arm). The vacuum gauges must be equipped with a digital (RS485) or analog (0-10V) pressure output.

<u>Requirement No. 3.7.10:</u> The horizontal mounting orientation is required for the pressure gauges due to the (mainly vertical) stray magnetic field around the tokamak.

The horizontal mounting orientation allows for easy installation of shielding against the vertical magnetic field.

<u>Requirement No. 3.7.11:</u> A free space of at least 3 cm around the vacuum gauges for the future installation of stray magnetic field shielding must be kept. The corresponding attachment points for this metallic (mu-metal and/or magnetically soft iron) shielding must be specified by the Seller no later than the Design Review.

Requirement No. 3.7.12: A universal control unit for the vacuum gauges and the secondary pump (preferred), or control units for each gauge and the secondary pump (alternatively) must be delivered by the Seller.

Requirement No. 3.7.13: A dedicated vacuum window must be used to separate the vacuum volume of the tokamak and the drum with the crystals of the spectrometer, allowing a high transmission of soft X-ray radiation (> 40 % over the entire measured spectral range) and a pressure difference of at least $\Delta p = 10^5$ Pa. If a beryllium window is used (not preferred), a low pressure difference ($\Delta p < 10^{-4}$ Pa) on it is required to ensure the safety of the tokamak.

Requirement No. 3.7.14: For both connections of the turbomolecular pump and the fore-vacuum pump with the main spectrometer vacuum duct, the use of a DN 100 CF (knife-edged flange according to ISO 3669:2020) (UHV compatible) 4-way cross, blinded from the top, is prescribed, which allows the future realization of a vacuum bridge over the vacuum window.

The Seller is not obliged to deliver the vacuum bridge, if this is not a part of the proposed design for the Design Review. On the other hand, if the vacuum bridge is proposed, the vacuum scheme of the SXR spectrometer (mainly primary pumping channel) must be modified accordingly.

Location of the center of one 4-way cross on the Rowland circle is desirable for testing purposes, if allowed by the design of the vacuum duct.

3.8. Other spatial requirements

In later operational phases of COMPASS-U, the spectrometer will be moved further from the tokamak hall to a shielded diagnostic room. Since the floor of the diagnostic room is located above the midplane of the tokamak, the observation of the plasma will be realized by an oblique view through a 1.5 m thick concrete wall. This view is spatially fixed and the available space is constrained by the floor of the diagnostic room and by a concrete block located 1 m above.

The Seller is not requested to design a special vacuum duct of the SXR spectrometer (this task will be realized by the Buyer in future), only the next requirements must be met so that the measuring part of the SXR spectrometer can be also used in the shielded diagnostic room.

Requirement No. 3.8.1: The SXR spectrometer, when it is located in the shielded diagnostic room and will have its crystals placed at a distance of 11 m from the plasma core and the equivalent diaphragm to the gate valve (DN 100 CF (knife-edged flange according to ISO 3669:2020)**) will be located at a distance of 1.7 m from the plasma core (on the optical axis of the SXR spectrometer), must fulfill the same requirements for spectral range and spectral resolution as for the location of the SXR spectrometer in the tokamak hall.**

Requirement No. 3.8.2: The space below and above the optical axis, used by components of the SXR spectrometer in its drum section (with crystals, crystal positioner and crystal

mount), spectrometer arm and detector, must not exceed 0.3 m (below) and 0.5 m (above), respectively.

It is highly desirable to have the required space below the optical axis, used by components of the SXR spectrometer in its drum section (with crystals, crystal positioner and crystal mount), even smaller, i.e. about 0.20-0.25 m.

Requirement No. 3.8.3: The vacuum duct between the crystal of the SXR spectrometer and the tokamak must be disconnectable closer than 1 m from the crystal and contain a vacuum CF flange (knife-edged flange according to ISO 3669:2020).

In the future, this vacuum connection will allow the SXR spectrometer to be easily moved from the tokamak hall to the shielded diagnostic room and reconnected to another vacuum duct.

3.9. Unsorted requirements

Requirement No. 3.9.1: The detector position must be well stabilized with respect to the (Bragg) crystal position to ensure resistance to vibrations.

Requirement No. 3.9.2: The SXR spectrometer must contain an adjustable aperture located near the bellows in the vacuum duct, limiting the vertical view of the SXR spectrometer. The vertical opening of the aperture must cover the range of at least 10 - 80 mm, while keeping the horizontal (opening) size at 100 mm (the horizontal view not limited by this aperture). The aperture must be remotely controlled.

Requirement No. 3.9.3: The spatial axis of a measurement performed by the detector for all delivered crystals for the entire spectral range of their use in the spectrometer must be provided by the Seller. If the only spatial axis given by the design (calculated) is delivered, the Seller is obliged to provide clear instructions on how such an axis can be set repeatedly.

Requirement No. 3.9.4: The spectral axis of a measurement performed by the detector for all delivered crystals for the entire spectral range of their use in the spectrometer must be provided by the Seller. If the only spectral axis given by the design (calculated) is delivered, the Seller is obliged to provide clear instructions on how such an axis can be set repeatedly.

Requirement No. 3.9.5: The wavelength dispersion (instrumental broadening) of a measurement performed by the detector for all delivered crystals for the entire spectral range of their use in the spectrometer, given by the design (calculated), must be provided by the Seller.

Requirement No. 3.9.6: Data required for the absolute calibration - the Seller is obliged to provide data sheets of optical properties (relevant transmittance, reflectance or quantum efficiency) for all used optical elements such as vacuum windows, filters, crystals and a detector for the entire spectral range of their use in the spectrometer. It is required that the provided specifications, together with ray tracing (ray tracing will be

done by the Buyer in future), enable the conversion of the measured signal to the spectral radiance of the measured plasma in [W/nm/sr/m^2].

3.10. Harsh environment in the tokamak hall of COMPASS-U

The SXR spectrometer will be operated during high-temperature plasma discharges of COMPASS-U and exposed to a harsh environment around the tokamak (stray magnetic field, gamma and neutron radiation). However, the spectrometer is planned to be located in the tokamak hall only in early operational phases of COMPASS-U, when low neutron and gamma radiation fluxes are expected. In later operational phases with the full performance of the tokamak, when high radiation fluxes can appear, the spectrometer will be moved further from the tokamak hall to a shielded diagnostic room. In this section, the maximum magnitudes and fluxes in the tokamak hall of COMPASS-U are provided to give an overview of the worst possible conditions around the spectrometer, however, the (neutron/gamma/stray magnetic field) shielding itself is not the subject of this tender.

The stray magnetic field will be temporarily present around the tokamak in the time proximity of a discharge (< 10 s). Its major component near the tokamak midplane has a vertical direction. For engineering purposes, the dipole approximation of the maximum possible stray magnetic field (considering plasma disruptions) is often used: max. 60 [mT] * (R[m]/ 3)$^{-3}$, where R is the distance from the torus axis, i.e. about 60 mT at 3 m, 38 mT at 3.5 m, 25 mT at 4 m and 13 mT at 5 m. Calculations of typical stray magnetic fields give only 10 mT at 4 m and 5 mT at 5 m.

<u>Requirement No. 3.10.1:</u> A free space of at least 3 cm around sensitive parts of the SXR spectrometer for the future installation of stray magnetic field shielding must be kept. The corresponding attachment points for this metallic (mu-metal and/or magnetically soft iron) shielding must be specified by the Seller no later than the Design Review.

The neutron flux at the tokamak midplane expected during the maximum performance discharge of the early operational phases will not exceed 4.2*10^8 n/cm^2/s (near the gate valve). Considering 2000 discharges per year with 1.8 s neutron rate flattop, the neutron fluence per year will be less than 1.6*10^{12} n/cm^2/year (near the gate valve of the SXR spectrometer). The calculated neutron fluxes near the tokamak hall walls are still about 5x lower. Induced gamma fluxes are always roughly an order of magnitude lower than the neutron fluxes. The plasma performance of COMPASS-U will be gradually increased and at the first manifestations of the influence of hard radiation, the SXR spectrometer will be locally shielded or moved away from the tokamak hall to the shielded area.

<u>Requirement No. 3.10.2:</u> The Seller is obliged to inform the Buyer of the fact that any component of the spectrometer could be sensitive (its functionality could be modified) to or even damaged by the specified conditions in the tokamak hall of COMPASS-U, if it is known to the Seller.

3.11. Design Review

<u>Requirement No. 3.11.1:</u> The attachment points for the stray magnetic field shielding must be specified by the Seller no later than the Design Review.

<u>Requirement No. 3.11.2:</u> The attachment points for the vacuum duct of the SXR spectrometer and any other components of the SXR spectrometer (if relevant) must be specified by the Seller no later than the Design Review.

<u>Requirement No. 3.11.3:</u> All dimension and other parameters of the SXR spectrometer required for the design of the tilting table, e.g. including the weight distribution in the SXR spectrometer, must be specified by the Seller no later than the Design Review.

<u>Requirement No. 3.11.4:</u> The Seller is obliged to provide the Buyer with the final design of the SXR spectrometer for the Design Review within 12 weeks after the Contract becomes effective. The final design must include a detailed design of the SXR spectrometer, including a description of all used components and accessories containing all important dimensions and used materials. All interfaces and outer boundaries must be drawn in 3D software and corresponding STEP-files must be provided to the Buyer. All provided materials and documentation for the Design Review must be in English.

To avoid misunderstandings and inapplicable design proposals, the Seller is encouraged to immediately contact the Buyer in case of any ambiguities or suggestions for unusual solutions.

<u>Requirement No. 3.11.5:</u> The Buyer will provide the Seller with confirmation (e-mail from the Buyer is acceptable) of the successful Design Review immediately after the Seller has resolved all objections to the submitted final design of the SXR spectrometer. Only the successfully passed Design Review establishes the right to pay the corresponding advance payment to the Seller, see Article 4.8. of the Contract.

3.12. Documentation

<u>Requirement No. 3.12.1:</u> The Seller is obliged to provide complete documentation for the SXR spectrometer as well as for all supplied accessories / components of the SXR spectrometer, where this is applicable, e.g. the detector, pumping system, vacuum window, spectral filter, set of the (Bragg) crystals and provided software including all APIs. It mainly represents operational manuals, data sheets, instructions for manipulation, maintenance and safety instructions, service manual and passed and prescribed checks / revisions (e.g. electrical).

It is expected that the Supplier also provides results of a) at least basic tests of the vacuum cleanliness of the SXR spectrometer vacuum duct, specified in the attached document "COMPASS-U Vacuum Requirements", b) measurement of the helium leak tightness $\leq 10^{-10}$ Pa.m^3/s for the UHV part of the vacuum duct (the vacuum parts of the SXR spectrometer that will be directly connected to the vacuum volume of the tokamak vacuum vessel), c) pumping both the vacuum parts of the SXR spectrometer.

Requirement No. 3.12.2: **The Supplier is also obliged to provide the actual (real) detailed design of the SXR spectrometer, including a description of all used components and accessories containing all important dimensions and used materials. All interfaces and outer boundaries must be drawn in 3D software and corresponding STEP-files must be provided to the Buyer.**

Requirement No. 3.12.3: **All provided documentation must be in English.**

3.13. Delivery conditions and Detailed Itemized Budget

Due to the complexity of the SXR spectrometer, representing a large instrument composed of many components and accessories of different nature (some of them can be very sensitive), it is assumed that the SXR spectrometer can be delivered in parts. Some of the delivered parts can represent already pre-assembled components of the SXR spectrometer, some can be delivered separately. It is expected that the Seller will consequently provide free-of-charge support for the first commissioning of the SXR spectrometer and its accessories / components at the place of delivery specified in the Contract.

Requirement No. 3.13.1: **The Seller is obliged to provide a Detailed Itemized Budget of the SXR spectrometer and its components / accessories already within the Bid. The Detailed Itemized Budget can include physical components of the SXR spectrometer, its logical parts or assemblies, mainly these listed in Article 3.1. Main components of the SXR spectrometer of the Technical Specification, or other deliverables such as the software including APIs, and the final design of the SXR spectrometer. The final design of the SXR spectrometer is accepted as the delivered item only if it successfully passed the Design Review, i.e. the Seller has resolved all objections to the submitted final design of the SXR spectrometer.**

Delivery of the entire SXR spectrometer or its parts is confirmed in the Handover Protocol(s), as specified in Article 3.5 of the Contract.

Requirement No. 3.13.2: **The necessary prerequisites for the "Individual Part Handover Protocol of Acceptance" are**

a) All requirements defined in the Technical Specification relating to the Individual Part (delivered item) are met. Complete documentation relevant to the Individual Part (delivered item) is provided.

b) The Individual Part (delivered item) corresponds to the specification in the Final Design.

c) All other requirements defined in the Technical Specification and in the Contract are in accordance with the acceptance of the Individual Part (delivered item).

d) The Individual Part (delivered item) was delivered to the representative of the Buyer to the place of delivery without any defects, except the case specified in Article 3.10 of the Contract.

<u>Requirement No. 3.13.3:</u> The necessary prerequisites for the (total) "Handover Protocol of Acceptance" are

a) All requirements defined in the Technical Specification are met.

b) The SXR spectrometer and all its components /accessories correspond to the specification in the Final Design.

c) All other requirements defined in the Technical Specification and in the Contract are met.

d) The SXR spectrometer and all its components /accessories were delivered to the representative of the Buyer to the place of delivery without any defects, except the case specified in Article 3.10 of the Contract.

3.14. Warranty conditions and post-delivery support

<u>Requirement No. 3.14.1:</u> The warranty period must be at least 24 months, excluding very sensitive optical elements (e.g. CCD chip, (Bragg) crystals, thin vacuum window), which must be explicitly defined by the Seller. Special warranty conditions can be set by the Seller but must be done explicitly for each such an item.

<u>Requirement No. 3.14.2:</u> The Seller is obliged to provide free-of-charge support for the first commissioning of the SXR spectrometer and its accessories / components at the place of delivery specified in the Contract. The support must include a) training in assembling, using and operating the spectrometer and all its accessories and components for the Buyer staff of at least 2 persons for at least 3 days, done not later than in 1 year after the complete delivery of the SXR spectrometer (i.e., done not later than in 1 year after signing of the Handover Protocol of Acceptance); b) online consultations for questions of a technical nature and the implementation of the supplied software including APIs in up to 1 year after the complete delivery of the SXR spectrometer.