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# Startup impurity diagnostics in Wendelstein 7-X stellarator foreseen in the first operational phase

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ABSTRACT: An essential element for stationary stellarator operation is the understanding of the impurity transport behavior. Neoclassical theory predicts an impurity transport towards the plasma core for the standard ion root regime in stellarators [1,2]. The performance of a quasi-stationary device like Wendelstein 7-X stellarator (W7-X, presently in the commissioning phase in Greifswald, Germany) could be limited in case of strong impurity accumulation. Therefore, a set of plasma diagnostics is foreseen to obtain key experimental quantities for the neoclassical transport modeling as ion temperature profile, density gradients and impurity concentration [3]. The core impurity content is monitored by the High Efficiency eXtreme ultraviolet Overview Spectrometer system (HEXOS) [4], covering the wavelength range 2.5–160 nm (intermediate ionization states of all relevant heavy intrinsic impurity species) with high spectral resolution and a time resolution of 1 ms, adequate for transport analysis. Impurity radiation at shorter wave lengths (4 nm – 0.06 nm) will be monitored with the SX pulse height analysis system (PHA) [5]. The ion temperature profile can be deduced from inversion of data from the High Resolution X-ray Imaging Spectrometer (HR-XIS), which measures the concentration and temperature of argon tracer gas in helium-like ionization stages [6-8]. A second X-ray Imaging Crystal Spectrometer (XICS), which will additionally provide the poloidal ion rotation velocity, is under preparation [8,9]. The total radiation will be measured by two bolometer cameras [10,11]. The status of the impurity diagnostics for the first operational phase in W7-X is summarized in this paper and an outlook for the next experimental campaign is given.

KEYWORDS: Stellarator; Impurity diagnostics; Wendelstein 7-X.

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## Contents

## 1. Introduction

Advances in the understanding of the impurity transport in magnetic confinement fusion plasmas are of high importance especially for the stellarator line, since these devices are inherently capable of steady state plasma operation. Due to the 3D magnetic field geometry, there is no neoclassical temperature screening, which could help to avoid impurity accumulation as in axis-symmetric (tokamak) plasmas. Experimentally, favourable operating scenarios were found in stellarator and heliotron plasmas [2, 12, 13], that might allow a steady state plasma operation without an accumulation of impurities in the core and the associated high radiative losses and fuel dilution. It is therefore important to study the impurity transport very carefully with the aim to develop working scenarios for long pulse operation (in Wendelstein 7-X stellarator the pulse length is 30 min, only technically limited by the cooling capacity) and improve the theoretical understanding of the impurity transport.

A single diagnostic which has a sufficient spatial and temporal resolution and provides the density and temperature of the contained impurity species is not available. The existent individual plasma diagnostic systems can only deliver a subset of the required information for the characterization of the impurity transport in a fusion plasma. Either, the spectral resolution is sufficient to distinguish between the ionization states of the existent impurities, but the spatial resolution is very limited, or many spatial channels are available, but the spectral sensitivity does not allow a distinction between different ionization states. It is therefore necessary to operate a set of diagnostics and to combine the results. Accompanying integrated modeling of the impurity transport is essential in order to extract the relevant transport quantities from the measured data [11].

## 2. Technical boundary conditions and challenges

In magnetic fusion experiments with electron temperatures in the range of 0.1–10 keV and electron densities in the order of $10^{19}$–$10^{20}$ $m^{-3}$ the typical impurity ions (carbon, oxygen, copper, iron) have strong emission lines in the VUV and XUV wavelength range (1-200 nm). The design of spectroscopic measurement equipment for emission lines in this wavelength range is complicated by the absence of suitable window materials. Therefore, VUV diagnostics need a direct connection to the vacuum of the plasma vessel and must comply with the strict UHV requirements of W7-X (base pressure < $10^{-8}$ mBar, leak rate < $10^{-6}$ mbar l/(s $m^2$)).

In addition to the general requirements of components in close vicinity to the W7-X stellarator torus such as the use of low Cobalt materials (ideally below 500 ppm) and low magnetic permeability materials (ideally $\mu_r < 1.01$), the microwave stray radiation needs to be considered in the diagnostic design. Depending on the distance to the ECRH launchers and the heating scenario, the diagnostic components must be capable to withstand high power fluxes of up to 50 $kW/m^2$ microwave stray radiation over a time span of 30 min. In case of VUV spectrometers, the small entrance slits can shield delicate parts inside the spectrometer from overheating by the stray radiation.

Halogen-free insulation material (including cable insulation) should be selected for the installation in the torus hall in order to reduce the release of toxic and highly reactive gases in case of fire. Furthermore, components installed in the torus hall should have remote handling capability, since the access to the torus hall during experimental campaigns is limited. For the first experimental campaign in 2015 (OP 1.1, cf. Ref [14]), this requirement is relaxed since a daily evening access to the torus hall is foreseen.

## 3. Signal quality and electrical grounding

The grounding concept of W7-X foresees a meshed topology. For many diagnostics directly attached to the W7-X vacuum vessel (examples are HEXOS, PHA, and HR-XIS detailed in the following sections) it was decided to implement a local grounding island in order to reduce ground loops and electronic pick-up noise, which would constrain the achievable signal to noise ratio of the measurement data. These grounding islands are connected via a single cable to the electrical grounding bar. All components (racks, diagnostic support structure) have to be insulated from the aluminum platform (utilizing GRP-Plates + GRP sockets (GRP: *glass-fibre reinforced plastic*)). The beam line towards the W7-X port contains an electrical break, made from polyether ether ketone (PEEK) sealing between two conflate flanges. Since PEEK is a good absorber for the microwave stray radiation, the seal is protected by a metal housing on the vacuum side with a small slit (0.5 mm) for the electrical isolation and pumping capability avoiding virtual vacuum leaks (cf. Fig 1).

## 4. Status of impurity diagnostics

In the following sections, we focus on the diagnostics, which will be available for impurity measurements for OP1.1.

### 4.1 Pulse height analysis system (PHA)

The X-ray pulse height analysis system (PHA), which has been developed in collaboration between IPPLM (Poland) and the IPP, has been assembled and tested in the laboratory at IPPLM [5]. It is planned to transfer the diagnostic components to the W7-X site for final assembly with the beam line and support structure and installation in the torus hall in May 2015. The diagnostic is capable to measure lines of various impurity species, determine $Z_{eff}$, the central electron temperature and investigate supra-thermal tails in the spectra. The system measures along 3 lines of sight with adaptable energy band widths. The incoming radiation is filtered by Beryllium foils of different thicknesses (up to 500 µm). The foils can be exchanged with a pneumatically operated mechanism inside the vacuum. The apertures of the respective energy channels can be controlled with two crossed piezo-slits (max. width: 1.35 mm). The filtered radiation is measured with 3 silicon drift detectors (SDD) in an energy range from 250 eV (5 nm) up to 20 keV (0.06 nm). An X-ray photon entering the SDD creates electron-hole pairs in the silicon, yielding an electric pulse at the anode. The electric charge of the pulse is proportional to the energy of the absorbed photon. It is amplified and acquired in a digital X-ray processor with 4 channels. By appropriately setting the filters and apertures in order to optimize the count rate, an energy resolution better than 200 eV will be achieved [15]. The fluorescent light from a steel plate illuminated by an X-ray source located outside the vacuum chamber is used as an in-situ energy calibration source for the detectors. The characteristic lines of Cu, Ti, Ni and Fe are foreseen as calibration lines. Further information on the X-ray pulse height analysis system (PHA) can be found in Ref. [5].

### 4.2 Bolometer

Two bolometer camera systems with 32 channels for the horizontal bolometer camera (HBC) and 40 channels for the vertical camera (VBC) have been installed on W7-X. They are mounted on port plug-ins in order to position the cameras in close vicinity to the plasma thereby providing a wide viewing angle that covers the complete triangular plasma cross-section. Gold film resistive detectors are used, which have a high absorption coefficient from UV- to soft X-ray range. Active water cooling is implemented both in the aperture and detector holder in order to avoid over-heating and thermal drifts of the system. The detectors are protected from microwave stray radiation with a metal wire-mesh. The detector housing is additionally coated with microwave absorber for damping the stray radiation flux density caused by multiple reflections. By the combination of these counter measures, the microwave impact level at the detectors is reduced by a factor of over 300 in total, being negligible in comparison to the plasma radiation induced signal [10]. A spatial resolution of about 5 cm and a time resolution of 3 ms are the design values. The total radiative power loss as well as tomographic reconstructions of 2D emission profiles will be provided by the bolometer systems. Additionally, on the secondary detector arrays with 2 cameras, 8 channels, each covered with a 10µm-Be filter, are available for measuring the soft X-ray (>800eV) emission purely from the plasma centre. These SXR-channels, together with other spectroscopic diagnostics are dedicated to study impurity transport features based on impurity injection experiments [11].

### 4.3 High resolution X-ray spectrometer system (HR-XIS)

The imaging spectrometer has been developed at FZ Jülich and was in operation on the TEXTOR tokamak [6,7]. After the end of TEXTOR operation, the spectrometer has been donated to the W7-X project. Due to space restrictions in the torus hall, several modifications were required, including the rotation of the spectrometer chamber by 180° around the viewing port axis and changes to the support structure in order to avoid collisions with other components. A new beam line has been manufactured and the complete diagnostic was installed at the beginning of 2015 (cf. Fig 2).

For the first operational phase, the control of HR-XIS (vacuum system including a cryo-pump and several pneumatic valves for different operation scenarios) is implemented with a PC-controlled switchboard. The local stand-alone PC (not connected to the central W7-X control) can be operated from outside the torus hall via remote control over the network. The vacuum in the beam line is monitored by gauges connected to the central safety system, which also controls the main gate valve to the plasma vessel.

With the current detector setup (using 6 *Marconi 30* type back illuminated CCDs), a maximum of 6 lines of sight is available, which spread across the lower half of a poloidal plasma cross-section. The plasma radiation enters the spectrometer through a 50 µm Beryllium foil, which also seals the spectrometer vacuum from the W7-X vacuum. A spherically bent quartz crystal has been adjusted for Bragg-reflection at a wavelength $\lambda$ = 4 Å (resolution: 1*10-4 Å). In this spectral range, the ion and electron temperature (300 eV ...4 keV) can be deduced from the He-like Argon emission lines (K$\alpha$-spectrum) with a resolution of 90 eV, as well as the plasma rotation and Argon impurity densities [8]. For the measurement, a trace Argon background is required in the plasma (0.1% to 1 % relative to the background gas). The data from the Peltiercooled CCDs are acquired with frame grabbers on two PCs in the nearby electronics rack. The necessary integration time is of the order of 10 ms in order to achieve sufficient counting statistics. The measurement is synchronized with the central trigger system. The upload of the locally stored collected data to the data base will be done manually.

A major upgrade of the detector system is planned after OP 1.1, which will increase the number of lines of sight and possibly also the detection sensitivity. Moreover, the spectrometer is already prepared for a quick change of crystals: up to 6 of them can be installed simultaneously on a rotation mount [6]. The necessary adjustment of the relative position between crystal and detector in order to achieve the respective Bragg-condition is possible with an X-Y stage and the rotation of the mount, all three axis operated by step motors. The geometrical alignment needs to be done in advance for each crystal. The respective position coordinates are stored on the control PC. Thus, it will be possible to change the monitored wavelength region on a time scale of tens of seconds during long pulse discharges. The installation of other crystals will allow the observation of further spectra of He-like or H-like ionization states, e.g., of Iron or Sulfur, which extends the accessible temperature range of the HR-XIS diagnostic to more than 10 keV. This will provide valuable information for the impurity transport analysis of these elements in future campaigns.

### 4.4 X-ray imaging crystal spectrometer system (XICS)

In addition to the already installed HR-XIS, a second X-ray imaging spectrometer is under preparation in collaboration with PPPL (USA) [9]. The components are being procured and assembled in the Princeton laboratory. The mechanical support of the spectrometer at the W7-X port has already been assembled in the torus hall along with the spectrometer chambers, and spherically bent crystals. Final installation is expected to be completed by the end of July, 2015.

XICS uses a water-cooled Pilatus 300K-W hybrid-pixel CMOS detector (Dectris Ltd.) which provides a 1475 pixels in the spatial direction and 195 pixels along the diffracted spectral direction (pixel pitch of the detector is 172 x 172 $\mu m^2$). The dispersion of the system is 0.43 mÅ / pixel. The sight line geometry covers the upper half of a poloidal plasma cross-section from the core out to a normalized minor radius of 0.8, cf. Fig. 3.

XICS is designed to measure electron and ion temperature profiles with a high resolution of 20 eV and in addition to provide measurements of the poloidal plasma rotation with an accuracy of 5 km/s. The XICS will provide a spatial resolution of approximately 2 cm with a time resolution of approximately 5 ms. For OP 1.1 the He-Argon $K_\alpha$-spectrum will be measured. In future, a second wavelength region will be accessible by use of an additional crystal and a second detector to measure the H-Like Argon $L_\alpha$ and He-like Iron $K_\alpha$-spectrum simultaneously.

### 4.5 High-Efficiency XUV Overview Spectrometer (HEXOS)

The HEXOS spectrometer system is a dedicated development specifically for the W7-X stellarator and has been built in cooperation between IPP, FZ-Jülich and Horiba Jobin-Yvon (France). The system consists of 4 spectrometers equipped with toroidal holographic diffraction gratings, which span the VUV/XUV spectral range between 2.5 nm and 160 nm (with 0.026 to 0.18 nm resolution) [4]. For this, pairs of spectrometers are combined as a double spectrometer and share a common vacuum chamber. The two double spectrometers are mounted back-to-back and the respective sight lines cross in the center of the poloidal plasma cross section (Fig 4). The 4 spectra are acquired by means of 4 Cesium Iodide-coated multi-channel plates (MCP, the vacuum-air junction) and 4 linear diode arrays with 1024 pixels each located outside the vacuum. The spectrometers are directly connected to the W7-X vacuum. Each double spectrometer has adjustable slit widths and two differential UHV pumping stages are employed in order to protect the W7-X vacuum from air leakage in the spectrometer chamber. The two beam lines that connect the double spectrometers to the W7-X port each have a gate valve that closes, if the pressure difference between plasma vessel and beam line vacuum is too high.

The beam line pressure measurement for the release of the gate valve is fed into the W7-X central control system. As a safety measure to protect the delicate MCPs, the high power supply voltage is ramped down in case of an increase in the spectrometer chamber pressure. Moreover, the chamber is automatically filled with Nitrogen in such case, in order to avoid a degeneration

of the MCPs (due to humidity in the channels and CsI being hygroscopic), which would lead to a loss of the absolute intensity calibration of the spectrometers. In order to achieve the functionality of the HEXOS system, more than 4000 m of cables have been routed inside the W7-X torus hall between the HEXOS spectrometers, the two nearby electronics racks (containing the power supplies and control units for the spectrometer temperature stabilization and the control units for the step motors operating the entrance slits and internal valves of the vacuum system), and the 4 distant electronic racks outside the torus hall (Fig. 5).

The last mentioned 4 racks contain the data acquisition components (generation of timer pulses for the read out of the linear diode array, measurement signal digitization and transfer to the central data base), high voltage power supplies for the MCPs, the vacuum gauges and the diagnostic control (PLC) which is connected to the central diagnostic control.

For OP1.1, this spectrometer system will be used to monitor the impurity content in the core plasma. Although not integrated into the safety system of W7-X, the HEXOS spectra can be used to detect the occurrence of possible local overheating of components within the plasma vessel by observing the impurity ions created by such events, and can thus help to prevent damage to the machine or single components. While in this first stage no localization of the impurity source is possible, in later experiment stages a combination of HEXOS data with local impurity injection systems as those mentioned below can be used for more detailed transport studies in W7-X.

## 5. Prospects for the second experimental campaign and beyond

For the second experimental campaign (named OP1.2 [14]), which is planned to start end of 2016 and that will run for about 1 year, further impurity diagnostics will be prepared. This includes the soft X-ray tomography system XMCTS, which will be important for a closer look at possible radiation asymmetries with respect to the flux surfaces. A reconstruction of the whole triangular cross-section with a spatial resolution in the cm-range will be possible [16] by means of 20 soft X-ray cameras in a poloidal ring installed inside the plasma vessel. However, a discrimination in the energy range is not possible with this system, since the utilized silicon detectors (type AXUV) have a wide spectral sensitivity range (the optical wavelength range is filtered by Beryllium foils of 12.5 µm thickness in the pinhole cameras). The installation of further bolometer cameras at various toroidal locations is foreseen, which will be helpful for the identification of toroidal radiation asymmetries [10].

Furthermore, the light impurity monitor system (LIM) is planned to be operational in OP 1.2. This system consists of two Johann double-spectrometers measuring the concentration of several important indicator impurities: Boron layer status (after machine conditioning), Carbon concentration (plasma wall interaction, overload protection), Nitrogen (detection of air leaks) and Oxygen (inventory of water on the surface of the plasma vessel). The LIM system is prepared in the Eurofusion framework within a collaboration between the University of Opole, Poland and the IPP [17].

Additional to the set of diagnostics for the observation of (intrinsic) impurities, the laser blow-off system (LBO, Eurofusion collaboration with Consorzio RFX, Italy [18]) and the Tespel pellet injection (planned collaboration with NIFS, Japan [19]) system will be essential for detailed transport studies. The idea is to inject a known amount of impurity atoms into the core plasma in order to observe the dynamics of the (radial) distribution of the impurities.

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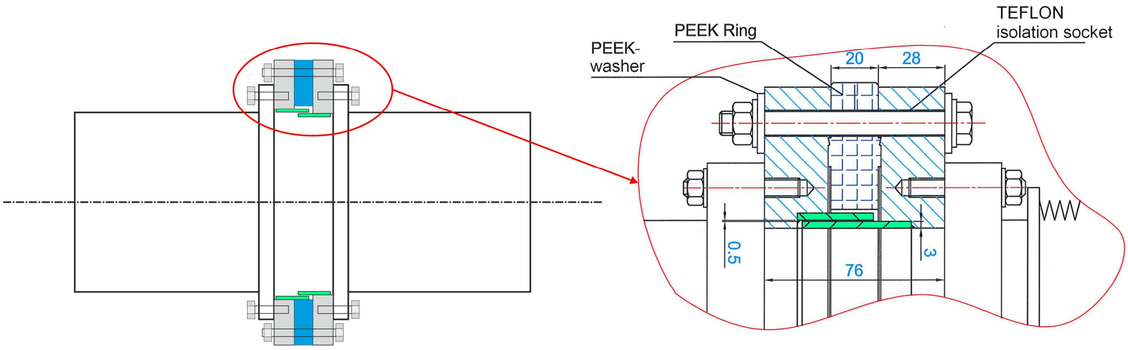


*Fig. 1: Electrical isolation break inside the beam line between two CF flanges. The compatibility with the microwave stray radiation requirements are met by the steel labyrinth housing (green colored), which shields the radiation from the PEEK sealing.*

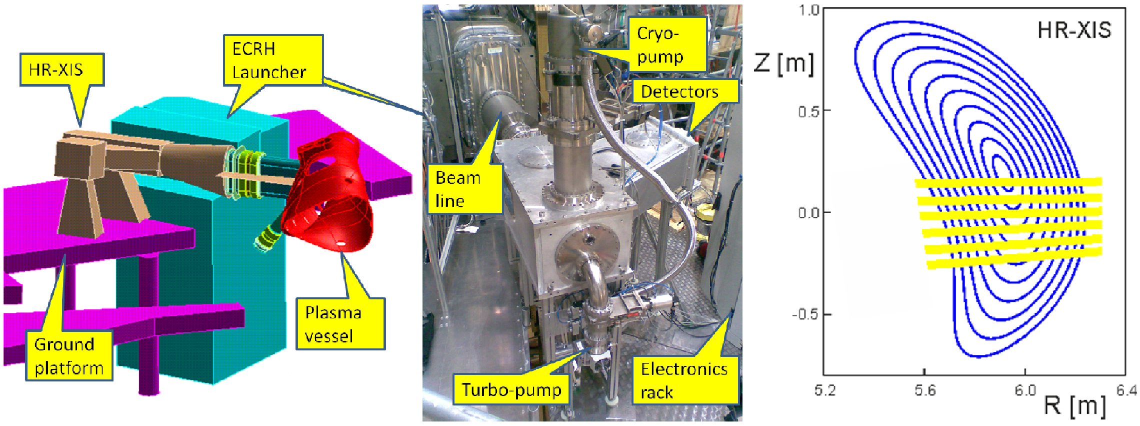


*Fig. 2: The installation location in an overview CAD model (left), photo after installation in March 2015 (middle) and the sight lines in the plasma cross-section (right).*

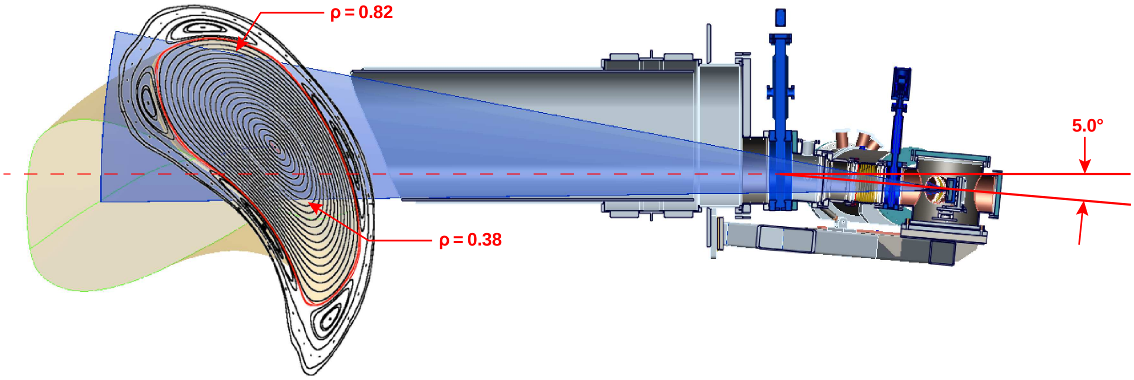


*Fig. 3: Viewing range of the XICS diagnostic.*

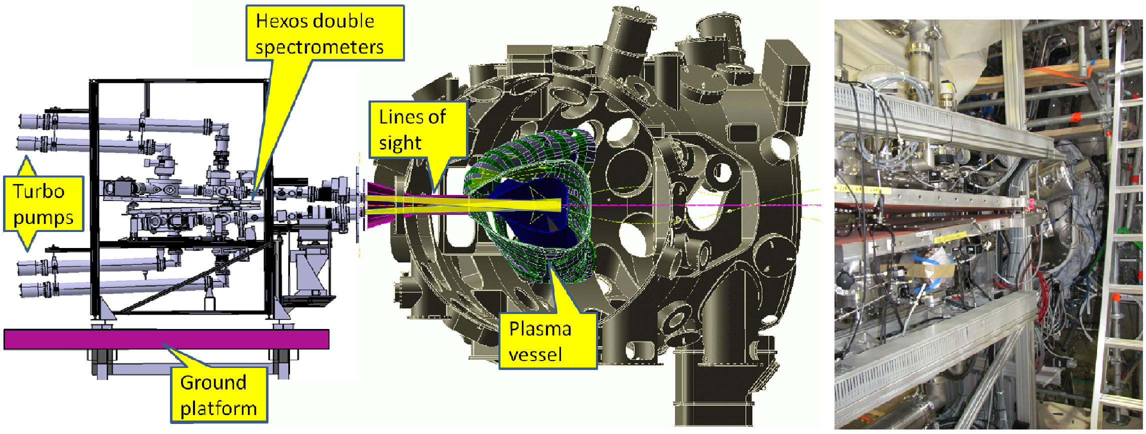


*Fig. 4: Sketch of the central lines of sight of the HEXOS double spectrometers. The plasma contour is shown in blue color.*

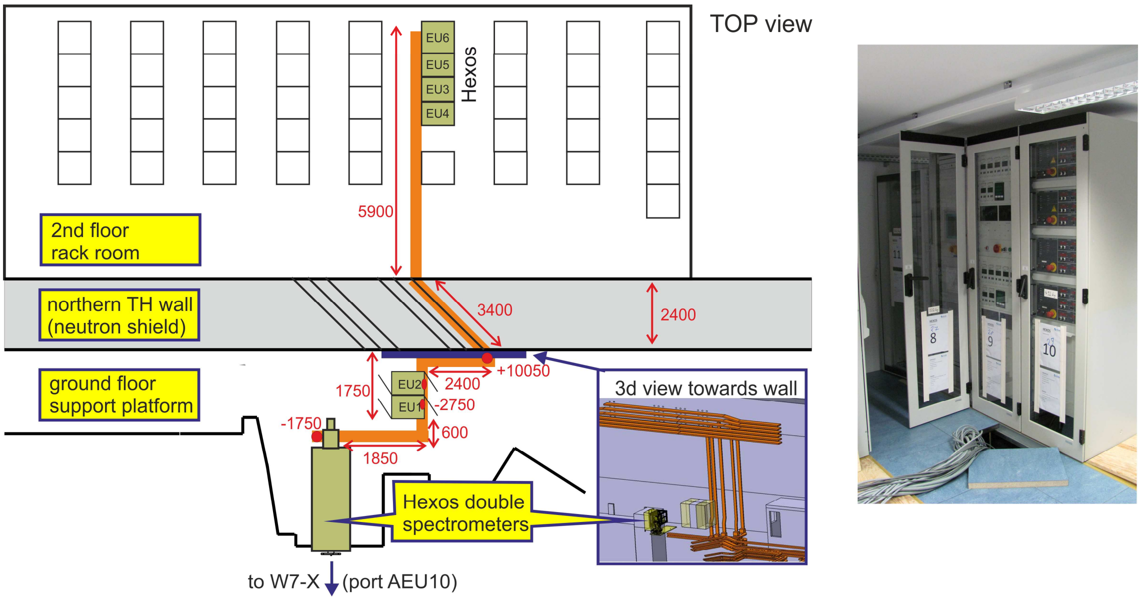


*Fig. 5: Sketch (top view) of the torus hall and neighboring rack room behind the torus hall wall. The HEXOS double spectrometers and rack locations are colored in blue. The cable routing paths are shown in orange, changes in height are marked by red circles (red numbers indicate distances in mm). The small inset shows the 3d situation in the torus hall (CAD) with cable trays (orange).*