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Engineering aspects of design and integration of ECE diagnostic in ITER

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Abstract. ITER ECE diagnostic [1] needs not only to meet measurement requirements, but also to withstand various loads, such as electromagnetic, mechanical, neutronic and thermal, and to be protected from stray ECH radiation at 170 GHz and other millimeter wave emission, like Collective Thomson scattering which is planned to operate at 60 GHz. Same or similar loads will be applied to other millimetre-wave diagnostics [2], located both in-vessel and in-port plugs. These loads must be taken into account throughout the design phases of the ECE and other microwave diagnostics to ensure their structural integrity and maintainability. The integration of microwave diagnostics with other ITER systems is another challenging activity which is currently ongoing through port integration and in-vessel integration work. Port Integration has to address the maintenance and the safety aspects of diagnostics, too. Engineering solutions which are being developed to support and to operate ITER ECE diagnostic, whilst complying with safety and maintenance requirements, are discussed in this paper.

1 Introduction

The main plasma ITER ECE diagnostic is planned to be used for the measurements of plasma electron temperature profile with good spatial and temporal resolutions [1-3]. Secondary objectives are to obtain information on non-thermal electron populations and the power loss due to ECE. One important requirement is to detect the Neoclassical Tearing Mode (NTM) when the island size is small enough to cause a deleterious effect on the confinement, i.e. before it reaches its saturated width and causes the mode locking, thus triggering a major disruption. The instruments of ECE on ITER are Michelson interferometry (O- and X-modes) and heterodyne radiometers (Ordinary, or O-mode, 122 – 230 GHz; eXtraordinary, or X-mode, 244 – 355 GHz for B_t = 2 – 5.3 T). The principal limitations of the system are restricted radial region of observation due to harmonic overlap and degraded spatial resolution due to relativistic broadening.

The ITER ECE system is divided into three main parts: the front-end, which collects the radiation from the plasma and which is located in the Equatorial Port Plug #09 inside the primary vacuum; the transmission system which transports the ECE emission from the front-end though the Port Interspace, Port Cell and the Gallery to a dedicated area located in the Diagnostic building; and the instrumentation.

Currently, two Domestic Agencies, US and India, are working in close collaboration with ITER Organization on design of ITER ECE diagnostic [1, 4]. Integration of the diagnostic in the tokamak complex is an engineering challenge [5]. ECE components are designed to be placed in a high radiation environment and expected to operate for a period at least 4 years without scheduled maintenance. This applies to in-port plug part of the system. Diagnostic integration in the tokamak is a very important task which requires interfaces with other systems, like vacuum vessel, buildings or remote handling. The latter is particularly important as the port plugs will have to be remotely handled during installation/removal, including refurbishment, environmental and functional tests in the Hot Cell Facility (HCF) outside the tokamak. Another very important design driver to the diagnostic is occupational safety to workers who will have to perform hands-on maintenance operations. The general layout of ECE system is shown in Figure 1. Many components are

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located in the inner, Port Interspace and outer, Cell, areas. These two areas of the Port Cell are radiation zones with substantially different (~ factor of 10) exposure levels but common atmosphere. The design of the diagnostic has to make a provision for minimizing worker's presence there for maintenance operations.

Various parts of ITER ECE systems will experience different load conditions, arising from electromagnetic events (during disruption), thermal and neutronic heating, and seismic events. There are other accidental loading cases, such as fire hazard in the port cell or gallery, which have to be taken into account during design, too. Finally, ECE in ITER has to be protected from microwave stray radiation by the ECH installation (170 GHz) and by other millimeter wave emission, like Collective Thomson scattering, planned to operate at 60 GHz.

Similar engineering constraints and design drivers are also relevant to other ITER mm-wave diagnostics, such as reflectometers and Collective Thomson Scattering system. These engineering constraints and requirements, as well as their applicability to the design of ITER ECE, are discussed in the following sections.

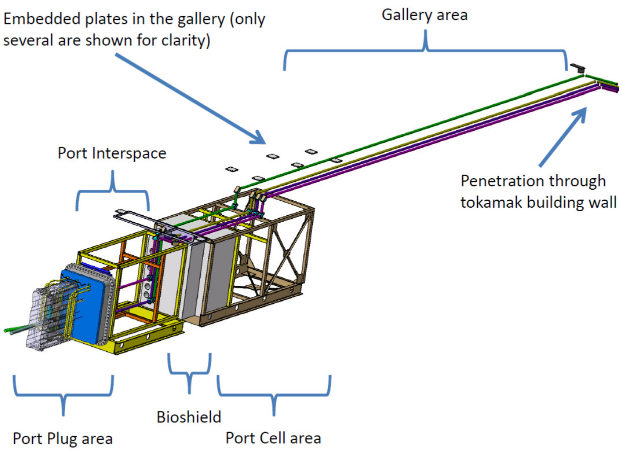

Figure 1. Current layout of ECE system from the port plug DSM (on the left) to the penetration through the tokamak building (on the right).

2 Structural Integrity of ECE diagnostic

The design of any port-based component shall follow the guidelines set up by ITER Load Specifications. There are two zones where different loading conditions apply: Port Plug area (includes Diagnostic First Wall (DFW), Diagnostic Shield Module (DSM), Port Plug (PP) structure with its closure plate) and ex-vessel area (includes interspace, bioshield and port cell).

The loads acting in these areas can be divided in:

- Inertial loads;
- Electromagnetic (EM) loads;
- Pressure loads: act on surfaces and include coolant pressure;
- Thermal and nuclear loads;
- Assembly or installation loads, e.g. pretension;
- Specific effects of other (dynamic) loads (e.g. vibration);
- Other types of loads (due to accidental events etc);
- Interfacing loads from ECH and CTS mm-wave radiation.

In the following sections, several loads which have to be taken into account in the ECE diagnostic design will be discussed.

2.1 Loads on in-port plug components

2.1.1 Electromagnetic loads

Electromagnetic loads due to plasma disruptions are due to Lorentz forces when electric current crosses magnetic field lines. These loads are typically body loads and act on nearly all conductive structures during transient events (e.g. plasma disruptions, Vertical Displacement Events (VDEs), and magnet current discharge). They can be expressed simplified as equivalent pressure loads on plates or as equivalent forces and moments on supporting points. In case of ferromagnetic materials used, Maxwell forces need to be also considered. Eddy current forces will be induced in the ECE front-end components, such as mirrors, shutter and hot source, due to these plasma disruption and the transient electromagnetics events. There are many different types of possible disruptions; the severity of a disruption depends on the poloidal location within the tokamak. At the equatorial port location, typically six main disruption cases are considered:

1. VDE_UP_LIN36 – Upward VDE with 36 ms linear current decay,
2. VDE_DW_LIN36 – Downward VDE with 36 ms linear current decay,
3. MD_UP_LIN36 – Upward Major Disruption with 36 ms linear current decay,
4. MD_DW_LIN36 – Downward Major Disruption with 36 ms linear current decay,
5. VDE_UP_LIN36 – Upward VDE with initially Slow and Fast current decay,
6. VDE_DW_LIN36 – Downward VDE with initially slow and fast current decay.

The worst case with respect to loading of EPP structure, as has been found in EM analysis which used input from DINA disruption studies, is a so-called MD_UP_LIN36 event. For the DSM with ECE front-end components, the worst case is identifies as a specific (not listed above) MD_DW16_OT_2010 event. The total force from EM events on in-port ECE components, such as shutters/ mirrors and first mirror mirrors, may reach tens of Ns. Contrary, DFW and DSM where ECE front-end is located may experience the total force of tens of kNs.

2.1.2 Seismic loads

Inertial loads are caused by accelerations due to gravity and seismic events. ECE in-port components will be attached to the DSM structure. The most important seismic events for ECE components are: **Category II Seismic Loads (SL-1)** – weaker seismic event, assumed to be equal to SL-2 / 3; **Category III Seismic Loads (SMHV)** – the most penalizing earthquake liable to occur over a period of about 1000 years, assumed to be equal to SL-2 multiplied by a factor 0.73 as first approximation; **Category IV Seismic Loads (SL-2)** – strong seismic event, defined by two spectra: SMS and PALEO spectra. All these loads and their spectra are described in ITER Load Specifications.

A convenient way to define the seismic action that the DSM (and thus the ECE diagnostic as well) is subjected to; is through the concept of design response spectrum. From the time history response at the point of interest in terms of accelerations, the local design seismic spectrum is built for each discrete frequency as the plot of the max amplitude of the response of a SDOF (Single Degree of Freedom) system in which this frequency correspond to the natural one and it is characterized by a damping ratio equal to the one at which the spectrum is defined. This calculation is performed for each of the three directions. Therefore, from global time history analyses on the machine response spectra are calculated in the upper internal point of EPP. These spectra should be used for seismic analysis of the ECE diagnostic equipment, which is located inside the EPP. Figure 2 gives typical spectra in radial direction for Equatorial Port 9 internal point.

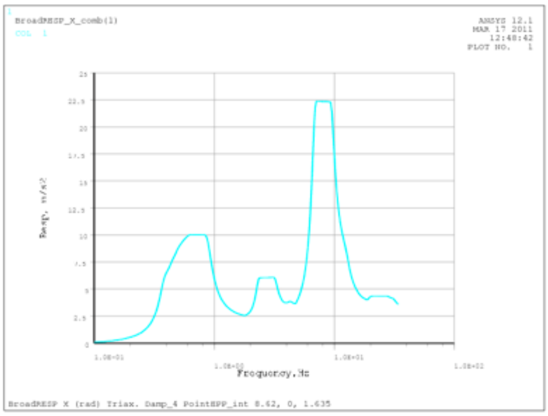

Figure 2. Example of spectrum calculated in the upper internal point of EPP which is used for seismic analysis of the ECE diagnostic equipment.

For the static equivalent seismic acceleration, the following conservative procedure is assumed: if the fundamental frequency is known, the seismic acceleration corresponds to the largest value of the local response spectrum for frequencies greater than or equal to the main natural frequency. This is justified if the system response is dominated by only one vibration mode. In order to take into account that the structure does not behave as a single degree-of-freedom an amplification factor 1.5 applied to the spectral acceleration. If the fundamental frequency is unknown, the seismic acceleration is conservatively taken as the maximum value in the spectra. Again, in order to take into account that the structure does not behave as a single degree-of-freedom, an amplification factor 1.5 is applied to the spectral acceleration.

2.1.3 Thermal loads

The EPP assembly including the DFW's and DSM's is heated by the plasma radiation and the nuclear heat during plasma operation. The ECE components themselves do not receive much of the plasma radiation because it is shielded from the plasma by the DFW, and only a first mirror is partly exposed to the plasma radiation through the solid angle aperture in the DFW with a viewing factor of about ~ 0.003. The surface thermal load on the DFW is limited to 0.35 MW/m^2 and ECE front mirrors may receive about 560 W/m^2 on oblique mirror and about 140 W/m^2 on radial mirror.

It is expected that large energy loads shall be generated during disruption mitigation. Massive Gas Injection (MGI) of Ne or Ar shall be used for mitigation of TQ energy loads. At 800 m^2 plasma surface area the average energy load shall be 0.375 MJ/m^2. The peaking factor for radiation is expected in the range 1-5 which could result in local peak energy loads in the range 0.375 – 1.875 MJ/m^2. This load shall be taken into account for the sensitive PFCs, such as First Wall apertures and mirrors. For the range of loads given above, one gets the range of loads on the first ECE mirror is expected to be between 1 kJ/m^2 - 5.3 kJ/m^2 (the Thermal Quench duration is 3 ms).

Neutronic heating is a volumetric one and is an important contribution to the overall heating of in-port plug ECE components. Since Conceptual Design Review, a redesign of the front-end optics to improve the neutronics has been performed [1]. One of the changes is the location of hot calibration sources inside the DSM, to avoid excessive activation on the port plug closure plate. However, the neutronic volumetric heating of the hot sources in this configuration will be increased, compared to the CDR design. At the preliminary design stage, after all analysis is completed, a decision about passive/ active cooling of the first mirror will be finalized. Currently, the first mirror is foreseen to be passively cooled, and the hot sources are foreseen to be actively cooled.

2.1.4 Other loads and load combinations

There are other loads which may affect the structural integrity of ECE components inside the Port Plug, such as maintenance loads, loss of coolant, thermal loads during baking etc. Moreover, for the structural analysis, not only single loads but load combinations have to be taken into account.

The ITER loading conditions are categorized, into four classes based on the expectation of occurrence: Category I: Operational Loading Conditions, Category II: Likely Loading Conditions, Category III: Unlikely Loading Conditions, Category IV: Extremely Unlikely Loading Conditions. Loads on Categories I to IV are within ITER Design Basis. In Table 1, an example of load combinations which may act on in-port plug ECE components is given for Categories I to III only (limited to plasma disruptions, seismic events and magnet discharge); the following events are indicated: MD: Major Disruption, MFD: Magnet Fast (current) Discharge, MFD I: Fast current discharge of PF and CS coils, VDE: Vertical Displacement Event (due to disruption), SL-1 Seismic Level 1 – defined by ITER for investment protection; SMHV («Séismes Maximaux Historiquement Vraisemblables») – Maximum Historically Probable Earthquake.

However, loads and their combinations for Category IV have to be analysed, too, because failure of components which are safety important may break the tritium confinement boundary, for example, at the closure plate (windows, feedthroughs etc), and cause plasma operations to stop and the operator to take serious mitigation/ recovery actions. Other loads, for example, those resulting from the pressure (loss of coolant, loss of vacuum etc) also have to be taken into account in the analysis.

Table 1. Example of typical load combinations for Categories I to III events (limited to seismic, plasma and magnet only) which have to be taken into account during design and analysis of ECE in-port plug components.

Seismic	Plasma	Magnet	Category	# of events
	MD I	MFD I	I	500
	MD II	MFD I	II	50
	VDE II	MFD I	II	50
SL-1	MD I		II	1
	VDE III	MFD I	III	-
	MD III		III	-
SL-1	MD II	MFD II	III	-
SL-1	VDE II	MFD II	III	-
SMHV		MFD I or II	III	-

2.2 Loads on ex-vessel components

Behind the Port Plug, outside the primary vacuum, the components of ECE diagnostic are placed on the so-called Interspace and Port Cell Support Structures (see Figure 1). These structures, in their own turn, are reacting on the tokamak building through the Remote Handling (RH) rails which are set up on the floor embedded plates. The typical path of loads for port interspace ECE components is illustrated in Figure 3. The main loads on the polarization splitter box and on the transmission lines in the port interspace and cell are gravity (seismic) loads, maintenance loads and fire loads.

Note that masses of the components of the ECE system are not a load unless accelerated. Acceleration of masses occurs due to several load cases, e.g. "Gravity", "Seismic Events", "Remote Handling", "Assembly" and “Load Drop”. In order to correctly apply these loads, the mass as well as the centre of gravity should be specified in the System Load Specification. Since the mass and center of gravity are an output of the design of the component, those values must be a reference in the specification and detailed values (coming from the design itself) should be used in the structural integrity analysis. Similar considerations are also valid for the transmission lines and their supports in the gallery and in the diagnostic building.

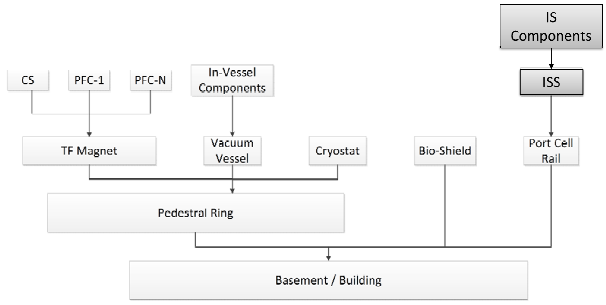

Figure 3. Path of main loads for ECE Interspace (IS) components (in bold) attached to Interspace Support Structure (ISS).

The Diagnostics Port Cells, including this of Equatorial Port 9 where ECE diagnostic components are located, contains some fire loads (e.g. epoxy materials, painting, insulating materials, cables), potential sources of ignition from both electrical and thermal origin (e.g. during welding and cutting operations during maintenance) and also the presence of oxygen. Then, an internal fire in a Port Cell is an envisaged event and considered as Category IV loading event. In addition, since the atmosphere of the Interspace is shared with Port Cell and because the door between the two compartments may be open during maintenance, fire in Interspace cannot be ignored. For a small ITER enclosure like the Port Cell, maximum temperatures are expected to be very high. For instance, it is assumed that maximum temperatures are around 700 degrees Celsius at 700 seconds which is higher than the limit fixed by the ISO 834 norms. Small rooms exhibit maximum fire duration of about 25 minutes. Elements penetrating port cell are however required to withstand fire during 2 hours. Average temperatures that can be expected far from the fire sources are always below 400 degrees Celsius. ECE diagnostic has to withstand the fire load and to be designed that its failure does not aggress safety barriers or any other Protection Important Components (PICs). The fire suppression system in the Port Cell is foreseen; however, it has different functions during maintenance (when human intervention is necessary) and during operation (no human presence in the Port Cell).

2.3 ECH and CTS interfacing loads

High power microwaves will be extensively used at ITER for a variety of purposes such as plasma break down assist, heating, current drive, NTM suppression but also as a probing beam for the Collective Thomson Scattering

(CTS) diagnostic. The ITER Electron Cyclotron Heating (ECH) system is designed to couple 20 MW of microwave power at 170 GHz into the plasma [6] while the probing beam of the CTS diagnostic launches 1 MW (2 MW upgrade possible) at 60 GHz. Depending on the particular ECH application and on the plasma conditions not all power is fully absorbed. In the case of CTS the objective is to scatter photons off the microwave beam and absorption is purposely minimised by choice of frequency and polarisation. In both cases substantial levels of non-absorbed microwave power result inside the vessel. Initially the power is contained in the directed beam that is shaped by the launcher but after a few passes through the vessel - and reflections off the walls - a more or less isotropic microwave stray radiation field builds up inside the vessel, referred to as stray radiation. Work is on-going to assess both the directed beam and the stray radiation.

2.3.1 Interfacing load from ECH

In the first plasma configuration, when blanket modules are not installed, the reflected EC beam can ***directly irradiate*** an area of the Vacuum Vessel. Note that Equatorial Port 9 with ECE is not planned to be installed for the first plasma; however, the ECH interfacing load is important for other ITER diagnostic systems. The EC power at start-up is about 6.7MW injected (with 8 beams). The beam will reflect onto the Low Field Side in the area of Equatorial Port 11, where the front-end of another microwave system, LFS Reflectometry, is placed. The peak intensity of the beam is expected to be at a maximum of 3MW/m^2 at the Low Field Side, assuming Gaussian profile of a beam. Start-up should pessimistically be considered to last for a period of 5.5 s. For the case of ***background power***, calculations have been performed to estimate the level of background EC power present in the Vacuum Vessel during start-up, giving a value of 30 mW/mm^2 per injected MW when the blanket is absent. This loading will not be seen at all locations around the vacuum vessel however, as it is not possible to predict the locations of the worst case background power, this figure should be assumed as a bounding case. During the pulse, ***non-optimal polarisation*** of the ECH beam will reduce the amount of power being absorbed in the plasma. In addition, the eventual total power of the EC system is expected increase to 20 MW. It is understood that up to 5% of the total power (i.e. 1 MW) may not be absorbed in the plasma under conditions of non-optimal polarisation. Currently, it is assumed that the maximum heat loading anywhere in the vessel due to non-optimal absorption is 1.25 MW/m^2, however it is not possible at this stage to define a maximum length of time for which the non-optimal absorption will occur.

It should be noted that, for the first plasma configuration, ECH Upper Port 16 will be used to inject high power RF. There will be a mirror on the central column, which will have HFS X2 mode. Thus, better absorption upon second path for burnthough is expected. The beam will be directed to Equatorial Port 18, were there will be no port plug at the first plasma. There is a proposal to install a beam dump in Equatorial Port 18 to avoid stray radiation. The combination of all this will aid to mitigate stray power issue for diagnostics which are planned to be installed for the first plasma.

In the standard plasma configuration, after blanket modules are installed, the peak intensity of the beam in case of ***direct irradiation*** will be a maximum of 3 MW/m^2 at the Low Field Side, also in the area of Equatorial Port 11. This beam will be incident on the first wall of the Blanket Modules. Due to uncertainty in the location of the second bounce at this stage of the design and the relatively large size of the second bounce high intensity region, it has to be assumed that the peak intensity will be incident upon a gap between Blanket Modules. Again, as in the first plasma configuration, start- up should pessimistically be considered to last for a period of 5.5 s. For the case of ***background power***, calculations have been performed to estimate the level of background EC power present in the Vacuum Vessel during start-up, giving a value of 20 mW/mm^2 per injected MW at the first wall as a worst case when the blanket is present. ***For non-optimal absorption***, the discussion and power limit presented for the first plasma configuration are also valid for the standard configuration, although it should be noted that the maximum heat loading will be seen at the first wall of the Blanket Modules, rather than directly on the wall of the Vacuum Vessel.

2.3.2 Interfacing load from CTS

The Collective Thomson Scattering (CTS) diagnostic uses a 60 GHz, 1.2 MW gyrotron probing beam delivering approximately 1 MW of microwave power into the vessel through Equatorial Port 12. Given the measurement principle - a tiny fraction of the beam is scattered off the electrons – the microwave power is not resonant and is not absorbed by the plasma. This gives rise to high levels of microwave power in the vessel.

The beam expansion of the CTS gyrotron beam is calculated and it is shown that after a double pass through the plasma the power density back at the closure plate of the Equatorial Port Plug 12 is of the order of 1.4 MW*m^{-2} for 1 MW CW gyrotron power (pessimistic case; see Figure 4), depending strongly on the curvature of the high field side wall. It is also assessed that power density of the directed beam after two passes through the vessel exceeds by far that of the isotropic power density caused by multiple reflections inside the vessel, estimated to be of the order of 10 kW*m^{-2} or even less.

Heating of the directed beam after a double pass through the vessel is assessed in a worst case scenario with a typical window (for example, $\varepsilon_r' = 3.8$ and $\tan\delta = 2.9E-4$) on the closure plate in the CTS port, i.e. at a power density of 1.4 MW*m^{-2}. The heating is independent of the window thickness and is about 0.6 K/s, given the specific window material properties. For 50% duty cycle gyrotron, and taking the cooling on the edge into account, the most likely temperature increase for quartz (fused silica) window is 0.1 K/s.

An assessment of heating of a conductor, vessel wall, by CTS isotropic stray radiation has been performed.

Given the small level of isotropic stray radiation by CTS, and the high reflectivity of the vessel wall with a massive heat sink, the heating by stray radiation is negligible. The loads on the closure plate due to isotropic stray radiation are expected to be two orders of magnitude lower, compared to that of ECW.

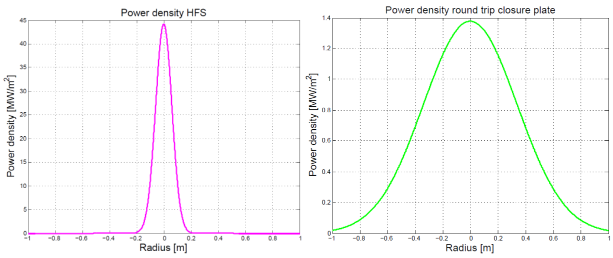

Figure 4. Actual power density of the CTS beam at the HFS (left) and after reflecting back into the port plug onto the closure plate (right). In the CTS case, there is almost no absorption by the plasma and the figures on the power density are indeed as in the case of an empty vessel.

3 Safety and maintenance aspects

ECE system shall provide adequate confinement feature to prevent from breaking confinement related to plant safety barriers (risk of tritium, dust and ACP (Activated Corrosion Products) contamination). The design of ECE components shall include all loading events for which the component performs a safety function. Similarly, all components shall also be designed such that operation, inadvertent actuation, failure or damage shall not prevent other equipment from performing their safety functions when required (see an example of fire hazards described in section 2.2).

ALARA (As Low As Reasonably Achievable) principle for personnel exposure to radiation has to be implemented when maintenance of ECE diagnostic is foreseen: time spent by personnel in radiation environment shall be as limited as reasonably achievable. This implies a modular approach for the integration of the Port Interspace and Port Cell. The diagnostics are mounted on structures in a workshop, and then installed in the Interspace and the Port Cell. This constraint also implies that the connections from one structure to the other shall be efficiently made and broken. It should be noted that the maximum occupational dose rates to workers in ITER is limited as follows: **individual (average) dose for workers** - 2.5 mSv/y (maximum reaches 10 mSv/h); **incidental situations** - less than 10 mSv/event; **hands-on limit** - dose rate < 100 μSv/hr; **collective dose** throughout ITER installation - 500 mSv/y. This means that only a very short duration human intervention to maintain ECE components in the Port Interspace/ Cell will be allowed during D-T phase of ITER operation (~ a couple of tens of hours for a whole port, including its servicing in the PPTF).

The refurbishment of in-port plug ECE components is foreseen in the Hot Cell Facility by means of RH tooling (no human intervention possible), whereas ex-vessel components located on the ISS/PCSS or directly attached to the closure plate can be refurbished hands-on or with assisted-manual tooling in a dedicated maintenance area in the Hot Cell Facility or at the Port Plug Test Facility. Components located in the gallery are assumed to be permanently installed.

4 Summary

An overview of most important loads applicable to the design of ITER ECE diagnostic is given in this paper. A special attention has to be paid to the safety aspects. In fact, efforts have to be given to minimize human exposure during maintenance of ECE components located in the Port Interspace and Port Cell. The role of the ECE diagnostic developers and the Port Integrator shall be to enforce a modular approach for the integration of the Port Interspace and Port Cell and to provide means to protect workers from radiation and to prevent chemical and/or radioactive contamination of port cells. Assisted-manual tools for handling equipment in the port interspace and the port cell can fulfil the demand to minimize human's exposure during planned or unplanned maintenance. Contrary, the design of in-port plug components shall be performed to be RH-compatible with robotic tools deployed in the Hot Cell Facility, where human presence is not planned.

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

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