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F4E-FPA-375-SG04: Assessment of stray-radiation protection needs for the PPR in-vessel components

This report covers the activities carried out in the scope of task T8.4 of SG04, in particular the result of the assessment of the need to develop stray-radiation protection measures for the PPR in-vessel components.

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FRAMEWORK PARTNERSHIP AGREEMENT FOR DIAGNOSTIC DESIGN AND DEVELOPMENT: PLASMA POSITION REFLECTOMETRY (PPR) (F4E-FPA-375)

ASSESSMENT OF STRAY-RADIATION PROTECTION NEEDS FOR THE PPR IN-VESSEL COMPONENTS (D15)

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Assessment of stray-radiation protection needs for the PPR in-vessel components	v1.0	In work	--	Initial version.

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LIST OF ACRONYMS

List of acronyms used in this document:

CTS	Collective Thomson Scattering
EC	Electron Cyclotron
ECE	Electron Cyclotron Emission
ECRH	Electron Cyclotron Resonance Heating
F4E	Fusion for Energy (European Domestic Agency for ITER)
FPA	Framework Partnership Agreement
HFS	High Field Side
ICD	Interface Control Document
ITER	International Thermonuclear Experimental Reactor
LFS	Low Field Side
PBS	Plant Breakdown Structure
PPR	Plasma Position Reflectometry
QRP	Quality Responsible Person
SG	Specific Grant
TRP	Technical Responsible Person
WBS	Work Breakdown Structure

1. APPLICABLE AND REFERENCE DOCUMENTS

Ref. #	Doc. #	Document title
		Applicable Documents
[AD-01]	F4E_D_3P45LM	Implementation Plan part of the Quality Plan for SG04
[AD-02]	ITER_D_G95536 v2.1	Interface Control Document (ICD) between Electron Cyclotron Heating and Current Drive (PBS 52) - Diagnostics (PBS 55)
		Reference documents
[RD-01]	F4E_D_2MXMTJ	PPR System Design Description Document (DDD)
[RD-02]	ITER_D_4D377D	Stray RF Power modelling in the Tokamak during EC operation
[RD-03]	ITER_D_RZHFWJ	Expected stray level for microwave diagnostics
[RD-04]	Oosterbeek et al.	Loads due to stray microwave radiation in ITER
[RD-05]	ITER_D_222W3R v3.1	ITER Material Properties Handbook: Electrical resistivity of Stainless Steel (SS) 316L(N)-IG
[RD-06]	ISBN: 978-1258326258	Gershon J. Wheeler – Introduction to Microwaves

2. EXECUTIVE SUMMARY

High power microwave systems shall be used both to assist ITER operation and as diagnostic tools. Some operational phases of these systems are characterized by low or no plasma absorption, resulting in high levels of stray radiation that may damage the Plasma Position Reflectometry (PPR) components installed inside the vacuum vessel. Additionally, Electron Cyclotron Emission (ECE) losses from the plasma continuously impinge high levels of broadband radiation on all in-vessel structures, in particular during high performance discharges. Stray radiation mainly impacts the in-vessel components as thermal loads. Depending on the level of these loads, protective measures such as active cooling or shutters might need to be implemented to prevent diagnostic components from overheating.

Here, we report on the assessment of the stray radiation load cases applicable to the ITER PPR in-vessel components and corresponding levels. We analyse the thermal effects of the applicable stray radiation loads and estimate the power that is coupled to the PPR waveguides, and absorbed in the vacuum windows that are part of the primary confinement barrier.

Due to the location of the PPR components, only the background and cross-polarised Electron Cyclotron Resonance Heating (ECRH) stray radiation are applicable to the PPR in-vessel systems. Similarly, only the Collective Thomson Scattering (CTS) background stray microwave power is applicable. The thermal effect of these loads as been analysed and we can conclude that it is negligible when compared with the thermal load arising from the plasma radiation.

The maximum power coupled to the PPR waveguides is estimated to be of the order of 300 W due to cross-polarised ECRH stray radiation. Assuming fused silica primary windows, this load results in about 11 W being absorbed in the windows, which may be considered negligible. Also, taking into account the dimensions of the PPR waveguides (rectangular ones 12x20 mm) and frequency of the ECRH (170 GHz) and CTS (60 GHz) radiation, we conclude that the risk of arcing or breakdown in the waveguides is also negligible.

ECE losses were not included in the set of applicable stray radiation loads due to the lack of a detailed assessment of these loads in ITER. Thus, we recommend that these results are reassessed when additional information about these loads is available.

Therefore, based on the assessment presented in this document we can conclude that there is no need to develop specific stray radiation protection mechanisms for the PPR components to be installed inside the ITER vacuum vessel.

3. INTRODUCTION

The PPR is planned to be used on ITER to measure the plasma edge density profile at four locations, known as gaps 3, 4, 5, and 6, distributed both poloidally and toroidally in the vacuum vessel (see [RD-01]). The system front-ends (antennas and waveguides) are installed either inside the port plugs of upper port 01 (gap 5) and equatorial port 10 (gap 3) or inside the vacuum vessel in the gaps between adjacent blanket shield modules (gaps 4 and 6) – gap 4 is located in the Low Field Side (LFS) and gap 6 in the High Field Side (HFS).

During ITER operation, high power microwaves will be used for a variety of purposes such as assisting plasma start-up using ECRH or as a probing beam for the CTS diagnostic. Some of the operational phases of these systems are characterized by low or no plasma absorption, resulting in high levels of stray radiation that may damage diagnostic components installed inside the ITER vacuum vessel, like PPR antennas and waveguides. Additionally, ECE losses from the plasma continuously impinge high levels of broadband stray radiation on all in-vessel components throughout the discharge, in particular during high performance discharges.

Stray radiation impacts the in-vessel structures and diagnostic components mainly as thermal loads whose levels depend on the absorption coefficient of the materials. Depending on the level of these thermal loads, protective measures such as active cooling or shutters might need to be implemented to prevent diagnostic components from overheating.

Here, we report on the work performed to assess the stray radiation load cases applicable to the ITER PPR in-vessel components and corresponding levels. The goal of this assessment is to support the decision regarding the need to develop stray radiation protection mechanisms for these components.

In the following sections, we analyse the thermal effects of the applicable stray radiation loads. Additionally, we estimate the power coupled to the PPR waveguides and absorbed in the vacuum windows that are part of the primary confinement barrier.

4. GLOSSARY OF TERMS

Term	Definition
Stray radiation	Radiation not serving any useful purpose.
Waveguide arcing	Phenomena where an electric arc is formed between the waveguide walls usually due to a voltage breakdown.

Table 1: Glossary of terms.

5. OBJECTIVES AND SCOPE OF THE WORK

The work reported here was carried out under task PPR.F4E-FPA-375.4.8.4 of Specific Grant 04 (SG04) of F4E-FPA-375. The main goal of this task was to assess the effect of the stray radiation loads on the in-vessel components of the ITER PPR system that supports the decision regarding the need to develop protection mechanisms for these components (see [AD-01]).

The task consisted of the following activities:

- Identification of the stray radiation loads applicable to the PPR in-vessel components;
- Assessment of the effect of the identified loads on the PPR in-vessel components;
- Decision on the need to develop stray radiation protection mechanisms for the PPR in-vessel components.

The scope of this task covers the in-vessel antennas and waveguides of the PPR systems of gaps 4 and 6 up to the port extension feed-outs, excluding the primary vacuum windows located at the end of the port extension feed-out (see §3.2 of [RD-01]).

6. STRAY RADIATION IN ITER

In ITER, stray radiation arises mainly from the operation of the ECRH and CTS systems and from ECE losses from the plasma. In this section, we will describe the various stray radiation load cases and identify the ones that are applicable to the in-vessel components of the PPR system.

6.1. Electron Cyclotron Resonance Heating (ECRH)

During ITER operation, up to 20 MW of 170 GHz O-mode ECRH power will be launched from equatorial port 14 (plus four other upper ports) and used for almost the entire duration of the discharges. The impact of the ECRH operation on the ITER diagnostics is defined in the Interface Control Document (ICD) between the ECRH system (PBS 52) and Diagnostics (PBS 55), where the worst-case load conditions are identified (see [AD-02]):

- Direct irradiation during plasma start-up:
  - Up to 3 MW/m^2 for a maximum time of 5.5 s
  - Localised on equatorial ports 11 or 17
- Cross-polarised beam reflected by the plasma:
  - Up to 1.25 MW/m^2, continuously
  - Assumed to be present on all first-wall apertures
- Background power during plasma start-up:
  - 20 mW/mm^2 (30 mW/mm^2 if the blanket modules are not installed, i.e., under first plasma configuration) per injected MW
  - Assumed to be present on all first-wall apertures

The PPR in-vessel systems are located on the LFS below upper port 1 (gap 4) and on the HFS directly in front of upper port 14 (gap 6). As such, the PPR in-vessel components are not directly hit by the ECRH beam or by any of its first three bounces (see [RD-02]). Therefore, only the cross-polarised beam and start-up background power loads are considered applicable to the PPR in-vessel systems.

6.2. Collective Thomson Scattering (CTS)

The ITER CTS diagnostic will operate from equatorial port 12 using a 1 MW 60 GHz X-mode beam. Currently, the internal interface between the CTS diagnostic and the other ITER diagnostics is not yet defined. Nevertheless, two worst-case load conditions are commonly identified in various documents (see [RD-03] and [RD-04]):

- Direct beam:
  - 25 MW/m^2 on the HFS
  - 3 MW/m^2 on the LFS after first bounce
- Background power: 7 kW/m^2, everywhere, continuously

As for the ECRH beam, the components of gaps 4 and 6 are not directly hit by the CTS beam. Therefore, only the background power load is applicable to the PPR in-vessel components.

6.3. Electron Cyclotron Emission (ECE) losses

As previously mentioned, ECE losses from the plasma will generate high levels of continuous broadband stray radiation, which will affect all in-vessel components. However, no detailed assessment is currently available regarding the expected ECE losses in ITER. Therefore, ECE losses are not considered in the analysis presented here.

7. EFFECTS OF STRAY RADIATION ON THE PPR IN-VESSEL COMPONENTS

Taking into account the discussion presented in Section 6, the stray radiation loads applicable to the PPR in-vessel components are listed in Table 2.

Load case		Power	Duration	Location
ECRH	Background power[1]	200 kW/m^2	5.5 s	Everywhere
	Cross-polarised beam	1.25 MW/m^2	Continuously	Everywhere
CTS	Background power	7 kW/m^2	Continuously	Everywhere

Table 2: Summary of the stray radiation loads applicable to the PPR in-vessel components.

In this section, we analyse the thermal loads on the PPR in-vessel components and the amount of power that is coupled to the PPR waveguides for the different load cases listed in Table 2.

7.1. Thermal loads

The stray radiation loads listed in Table 2 are specified as power densities. The thermal impact of these loads depends on the heat absorption coefficient of the materials used to manufacture the different structures and components located inside the ITER vacuum vessel. The heat absorption coefficient may be expressed as:

$$A = \left(\frac{4}{Z_0}\right)\sqrt{\pi f \mu_0 \rho} \tag{1}$$

Here, Z_0 is the impedance of free space, f is the stray radiation frequency, μ_0 is the permeability of free space, and ρ is the electrical resistivity of the material.

The PPR in-vessel components shall be manufactured of ITER Grade Stainless Steel (SS) 316L(N)-IG, which has an electrical resistivity of $94\mathrm{x}10^{-8}$ Ω/m at a temperature of 300 ºC (see [RD-05], Table 2). At this temperature, the absorption coefficient of the SS 316L(N)-IG for the 170 GHz ECRH stray radiation is A_{170}=0.0085. In order to account for the surface finish of the material we apply a safety factor of 2, resulting in an absorption coefficient of A_{170}=0.017.

The thermal loads affecting the PPR in-vessel components are then obtained by applying the absorption factor to each of the loads listed in Table 2. The obtained loads are listed in Table 3 – for 60 GHz stray radiation from CTS, where we needed to multiply the resulting thermal loads by the frequency correction factor of $(60/170)^{0.5}$.

Load case		Power	Duration	Location
ECRH	Background power	3.4 kW/m^2	5.5 s	Everywhere
	Cross-polarised beam	21 kW/m^2	Continuously	Everywhere
CTS	Background power	70 W/m^2	Continuously	Everywhere

Table 3: Summary of the thermal loads applicable to the PPR in-vessel components.

However, the PPR in-vessel components are not completely exposed to the stray radiation, since they are partially shielded by the blanket modules (see Figure 1). Hence, to determine the thermal loads impinging on the PPR components we still need to affect the loads listed in Table 3 by the cross-

[1] As specified (see [AD-02]), the ECRH power injected at plasma start-up is assumed to be 6.7 MW.

section of the apertures through which the antennas and waveguides of gaps 4 (~200x60 mm^2) and 6 (~180x40 mm^2) access the plasma. The resulting loads are listed in Table 4.

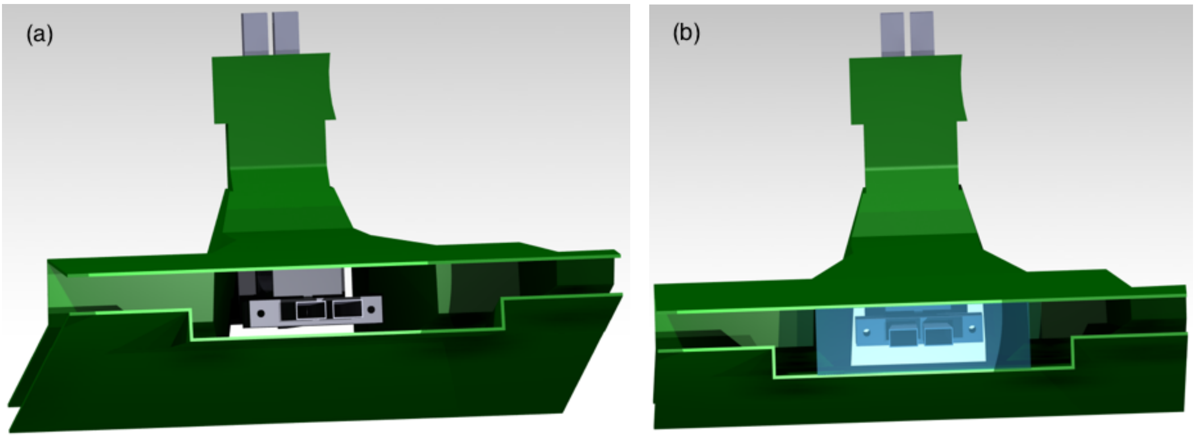

Figure 1: (a) PPR antenna setup of gap 4 between the blanket modules in rows #11 and #12 (green surfaces); (b) Cross-section (blue shaded) considered for the calculation of the thermal loads affecting the PPR antenna and waveguides.

Load case		Power	
		gap 4	gap 6
ECRH	Background power	40 W	25 W
	Cross-polarised beam	250 W	150 W
CTS	Background power	< 1 W	< 1 W

Table 4: Summary of the thermal loads applicable to the PPR in-vessel components, taking into account the dimensions of the gaps between blanket modules where the antennas and waveguides are located.

These loads are negligible when compared with the plasma radiation heat flux of approximately 500 kW/m^2 affected by the aperture cross-sections, which alone represents a thermal load for the components of gaps 4 and 6 of approximately 6 kW and 3.6 kW, respectively.

This conclusion can be confirmed by determining the additional thermal effect resulting from the stray radiation loads with respect to the plasma radiation load.

The heat flux between two surfaces i and j may be expressed by:

$$q_{ij} = \sigma \frac{\left(T_i^4 - T_j^4\right)}{\left(SR_i + GR + SR_j\right)} \quad (2)$$

where σ is the Stefan-Boltzmann constant, T_i and T_j are the temperatures, in Kelvin, of the surfaces i and j, SR is the thermal radiation resistance of each surface, and GR is the geometric resistance between the surfaces, taking into account the view factor between the surfaces[2].

The ratio between two heat fluxes q_{ij} and q_{ij}^* is given by:

$$\frac{q_{ij}}{q_{ij}^*} = \frac{T_i^4 - T_j^4}{T_i^{*4} - T_j^{*4}} \quad (3)$$

where T^* is the temperature of the surfaces with respect to q_{ij}^*.

[2] The view factor F_{ij} between surfaces i and j is defined as the fraction of radiation leaving surface i that is intercepted by surface j.

Rearranging equation (3) in order to T_i^*, we obtain

$$T_i^* = \left(\frac{T_i^4 - T_j^4 + QT_j^{*4}}{Q}\right)^{\frac{1}{4}} \tag{4}$$

where $Q = q_{ij}/q_{ij}^*$.

Considering:

- the heat flux due to plasma radiation alone $q_{ij} = 500$ kW/m^2
- an equivalent emitting surface temperature $T_i = 1455$ ºC (determined considering a black body radiating heat flux of $q = 500$ kW/m^2 to the surrounding space with a temperature of $T_j = 300$ ºC)
- the temperature of the receiving surface to be $T_j = T_j^* = 300$ ºC
- an additional heat flux of 25 kW/m^2 due to stray radiation[3], that is $q_{ij}^* = 525$ kW/m^2

and substituting in equation (4) we obtain $T_i^* = 1476$ ºC, which corresponds to a 21 ºC temperature increase from $T_i = 1455$ ºC, i.e., approximately 1.4%. Therefore, we can conclude that even the worst-case stray radiation load condition can be considered negligible from the thermal effect point of view.

7.2. Power coupled to the waveguides

To determine the amount of stray microwave power coupled to the PPR waveguides we need to consider the cross-section defined by the dimensions of the antenna (~25x14 mm). Table 5 gives a summary of the power coupled to the PPR waveguides for the different stray radiation load cases.

Load case		Power	Duration	Frequency
ECRH	Background power	70 W	5.5 s	170 GHz
	Cross-polarised beam	440 W	Continuously	
CTS	Background power	2 W	Continuously	60 GHz

Table 5: Summary of the power coupled to the PPR waveguides for the various load cases.

7.3. Power absorption on the vacuum windows

Part of the stray radiated power coupled into the PPR waveguides will be absorbed at the primary vacuum windows located just after the port extension feed-outs on upper ports 01 and 14. From Table 5, the worst-case load condition arises from the cross-polarised ECRH beam. Assuming that the primary vacuum windows are made of fused silica, the windows will absorb ~2.6% of the coupled power, resulting in a window load of about 11 W.

7.4. Risk of arcing and breakdown in the waveguides

Next, we analyse if the amount of stray microwave power coupled to the PPR waveguides is enough to cause arcing and breakdown inside the waveguides.

When a wave propagates inside a waveguide, an electrical potential develops between the waveguide walls. The maximum power that can be handled by a waveguide is limited by the voltage breakdown. For a rectangular waveguide with dimensions $a \times b$ operating in the TE_{10} mode at standard ambient temperature and pressure, the maximum power is given by (see [RD-06]):

$$P_{max} = 6\times10^5 ab(\lambda/\lambda_g) \tag{5}$$

[3] The 25 kW/m^2 stray radiation load corresponds to the combined power of background and cross-polarised ECRH beam.

where λ is the wavelength in free space and λ_g is the wavelength in the waveguide. Considering the dimensions of the PPR in-vessel waveguides of 20x12 mm and substituting in equation (5), we have $P_{max} = 1.43$ MW for the ECRH (170 GHz) radiation and $P_{max} = 1.428$ MW for the CTS (60 GHz) radiation.

If we consider a safety factor of 4, the power limit is reduced to about 350 kW. On the other hand, the power limit increases if the waveguide is inserted in vacuum, as in the case of the PPR in-vessel rectangular waveguides. Taking into account the worst-case load of 440 W due to the cross-polarised ECRH beam (see Table 5) we can conclude that the risk of arcing or breakdown in the PPR waveguides due to coupled stray microwave power is negligible.

8. CONCLUSIONS

Here, we report on the assessment of the stray radiation load cases applicable to the ITER PPR in-vessel components and corresponding levels. We analyse the thermal effects of the applicable stray radiation loads and estimate the power that is coupled to the PPR waveguides, and absorbed in the primary vacuum windows that are part of the primary confinement barrier.

Due to the location of the PPR components, only the background and cross-polarised ECRH stray radiation are applicable to the PPR in-vessel systems. Similarly, only the CTS background stray microwave power is applicable. The thermal effect of these loads has been analysed and we can conclude that it is negligible when compared with the thermal load arising from the plasma radiation.

The maximum power coupled to the PPR waveguides is estimated to be of the order of 440 W due to cross-polarised ECRH stray radiation. Assuming the primary vacuum windows are made of fused silica, this load results in about 11 W being absorbed in the windows, which may be considered negligible. Additionally, taking into account the dimensions of the PPR waveguides (rectangular ones 12x20 mm) and the frequency of the ECRH (170 GHz) and CTS (60 GHz) radiation, we conclude that the risk of arcing or breakdown in the waveguides is also negligible.

ECE losses were not included in the set of applicable stray radiation loads due to the lack of a detailed assessment of these loads in ITER. As such, we recommend that these results are reassessed when more detailed information about these loads is available.

Therefore, based on the assessment presented in this document we can conclude that there is no need to develop specific stray radiation protection mechanisms for the PPR components to be installed inside the ITER vacuum vessel.