Diamond Windows Diagnostics for Fusion Reactors – Updates of the Design

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I. INTRODUCTION

In order to ensure reliable operations, nuclear fusion reactors are often equipped with a set of Electron Cyclotron Heating and Current Drive (ECH&CD) launchers, capable of injecting highly localized microwave beams, for mitigating MHD instabilities like magnetic islands. Each launcher is fed by a number of transmission lines and, if D-T operations are foreseen, a suitable Tritium and vacuum barrier needs to be installed on each line.

In ITER for example, torus window assemblies are present in each waveguide [1,2]. Extremely high transmission is needed as absorption would lead to thermal failure of the window. There is thus the need for a material with very good optical, thermal and mechanical properties. This material is diamond. Today, by using Chemical Vapor Deposition (CVD) techniques it is possible to grow layers of diamonds over large areas and to use them as tritium / vacuum barriers inside high power microwave transmission lines. Diamond presents the aforementioned characteristics: the highest thermal conductivity in nature (3300 W/(m*K) for monocrystalline ^{12}C enriched diamond at room temperature [3]), meaning easier cooling even by indirect methods without diamond-water contact; a very low absorption in the microwave region (loss tangent as low as $2*10^{-5}$ for polycrystalline synthetic diamonds [4]) and a very large bandgap of 5.5 eV, resulting in very high electrical breakdown threshold) and it is almost insensible to the majority of chemical agents. Finally, diamond resists up to 1700 °C in an oxygen free atmosphere [5, 6].

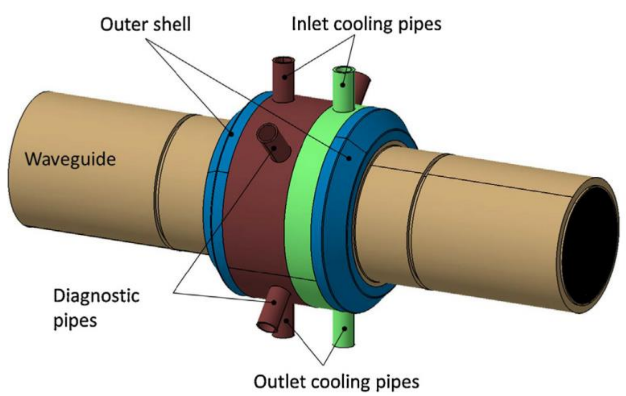

Fig.1 The diamond window assembly (as designed for ITER) in its original version, complete with waveguides section [7]. In brown, the cooling-diagnostic ring that will be subject to the modifications described in this work.

Although perfectly suitable for their intended use, considering the environmental conditions they will face and the complexity of nuclear fusion reactor operations, the windows require a constant monitoring of the operating parameters and conditions in order to ensure safe and reliable operation of the ECH&CD system. In this paper, the latest assessment study on a set of diagnostics to be part of the window assembly is shown. The required diagnostics include arc and tritium detection, microwave stray radiation (perpendicular to the main beam, scattered by possible cracks in the diamond disc), and pressure monitoring. The devices must have a compact, simple and flexible layout, with a rugged design, to maximize serviceability and durability. When multiple options are possible for some of the diagnostic systems tradeoffs were assessed. To accommodate the diagnostics previously mentioned, a new design for the ITER window housing was developed. The design of the original diamond window assembly underwent further developments from the beginning of this project and the new layout presented here integrates these updates with those related to the diagnostics. To validate the concepts, a test bench was developed to carry out measurements under conditions similar to the operative ones.

II. DIAGNOSTICS

The most critical diagnostic to be implemented in a diamond window assembly is the arc detection. Arcs may occur in the case of an electrical field build up and their effects are highly destructive for the surroundings. They can lead to the cracking of the diamond disc inside the window, impairing the transmissivity performances and opening leaks of tritium into the environment or on the gyrotrons side of the waveguides. Arcs will always travel in the direction of the microwave source (the gyrotrons of the facility) and although it is very unlikely that they will be able to travel back along the whole system (around 100 m), the damage generated will propagate with them [8, 9]. It is therefore mandatory to shut down the gyrotrons as soon as the arc event occurs: carbonization of the disc will rapidly degrade the optical properties of the window and the release of particles inside the waveguides will greatly dampen the transmission of the microwave beams.

While the insurgence of electrical arcs itself inside the transmission lines hardly poses any danger for the human staff of the reactor, tritium represents a serious biological hazard and needs to be detected. It is known that the decay radiation spectrum of the beta emitting hydrogen isotope is biased towards low energy electrons (with approx. 18 keV as maximum and 5 keV as average, with the peak emission at approximately 2.5 keV, see Fig.2) [10] and therefore itis not dangerous as long as it stays outside the human body.

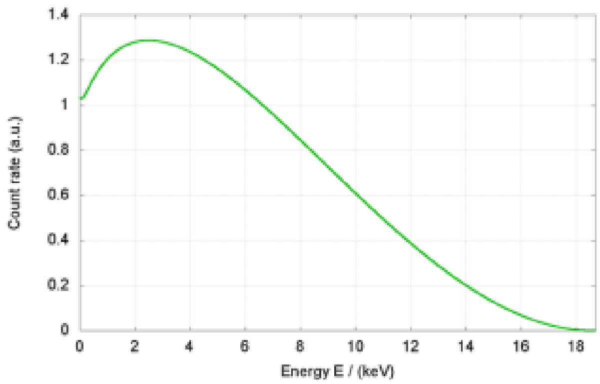

Fig.2 Tritium decay spectrum

Hydrogen binds with carbon and hydroxyl radicals, which results in absorption by the human body via ingestion, inhalation or through the skin. It also explosively reacts with the oxygen present in the air with minimal activation energy, which can cause catastrophic damage to both the plant and the human staff.

The third kind of diagnostic is meant to detect eventual cracks that may form in the windows, via microwaves sensible sensors. The presence of a crack would result in scattered radiation along the radial direction, perpendicular to the main axis of the waveguides. Cracks can become radiation absorption hotspots, promoting the incurrence of subsequent arcs. They can also lead to leaks of tritium along the gyrotrons side of the waveguide. It is therefore mandatory to detect the damage and shut down the closure valves and the beam power in the affected beamline.

Vacuum is mandatory inside the reactor and in the waveguides that bring power to the plasma. It is necessary to monitor the pressure: in case of air infiltration from the outside environment the plasma discharge is very difficult or impossible, depending on the quantity of impurities leaking inside the vacuum vessel.

III. Devices Technical Discussion

Arcs

The concept we propose is to use a fiber optic vacuum feed-through inserted in the outer ring of the copper cuff to bring the light signal to either an Avalanche PhotoDiode (APD) or a PhotoMultiplier Tube (PMT) coupled with a PIN diode. The first solution is more compact and rugged and should be the first choice. This configuration allows the detachment of the detector from the cuff, improving accessibility to the device. This kind of system has been used multiple times along a large variety of machines [8,9] and so its reliability is proved. An interlock system for the gyrotrons triggered by the signal coming from the light sensor is the final component of such a system.

Tritium

The most straightforward method to detect tritium is to exploit its beta radiation emission. There are various kinds of devices that are in principle adapted to this kind of detection, and one can divide them in three categories: gas counters, solid state detectors and scintillators. Again, the application in the fusion facilities requires ruggedness, radiation resistance, simplicity and the ability to operate in high temperatures and in vacuum conditions. Gas detectors (ion chambers, proportional and Geiger counters) detect the radiation by converting it in an electrical current via the generation of electron-ion couples inside a gaseous medium. Depending on the voltage applied between the electrodes, these phenomena may generate an exponential electron avalanche, boosting the sensibility and generating large current signals. Unfortunately, they are delicate devices, sensible to environmental changes and with a low sensibility to area ratio, given the low density of their detecting medium. In addition, they are sensible to all kind of radiation and can give false positive signals [11]. Solid state detectors work with a similar principle, where the electron-ion pairs are generated inside a crystalline medium instead of a gaseous one. Diamond can be the detector active material. It has exceptional resistance to radiation, to mechanical stress and chemical attacks. The higher density of the active material, compared to a gas medium, allows for smaller size sensor without sacrificing the detection capabilities. Their wide bandgap results in an extremely low dark current, making them suitable, along with the high thermal conductivity, for their use without cooling in a high temperature environment. Furthermore, their broadband optical transparency means that they are not sensible to light pulses, like those that may come from electric arcs. The 5.5 eV bandgap cancel all the signal coming from electron with less than that energy, although the percentage of electrons emitted through beta decay with such low energy is extremely low, there will be a considerable amount (about 10%) of accompanying secondary electrons given by shake-off processes. The detector will still require a bias electric field, in the order of 1.2 V μm^{-1}, with a typical thickness for a diamond sensor interface in 100 - 300 μm range [5, 6, 12]. Scintillators employ a different mechanism, and rely on the coupling with a suitable photodetector. The striking beta particle generates a photon in the scintillating material, that is therefore collected either by an optical amplifier (such as a PMT) or directly by a photodiode. Classic Si photodiodes at zero bias represent the simplest solution, given that such a device does not have any amplification stage in the detector itself. Unfortunately several factors reduce the feasibility of such devices in a copper cuff environment. Extremely low energy beta electron will generate fewer photons in the scintillation material, with an even smaller number of them hitting the detector and therefore generating a very low signal [11]. The number of beta particles is quite low, considering that the activity of tritium is measured to be 357 TBq/g [13], with the total amount of tritium inside a reactor like ITER being roughly 250 grams per day. The temperature range inside the copper cuff oscillates in a range between 20 and 70

°C and even the best photodiodes at those temperatures have large dark currents. They require strong temperature stabilization, given also the nonlinear response of photodiodes over increasing heat.

Microwaves

The detection of scattered millimeter waves requires the use of collecting horn antennas. Each antenna will be connected to an independent detector channel. Given the high power generally involved in radiation scattered from a MW power level system, we can avoid the use of superheterodyne system, going for a Direct Detection method. In such system the signals are first preselected with a band pass RF filter and then amplified with a fixed gain low noise amplifier. The signals get directly down converted to in-phase (I) and quadrature (Q) baseband signals. After demodulating RF signals, individual channel selection occur via additional filtering. Missing the intermediate frequency (IF) stage of the superheterodyne systems, the resulting device is much simpler and compact. The absence of filtering before the demodulator requires, though, a high dynamic range (~ 80 dB). Demodulators with this kind of performance are commercially available and able to operate in a vast range of temperatures, making them the ideal choice for this application [14].
In order to proof the concepts, a test bench with built-in horn antenna has been realized (Fig.3). The test bench replicates the copper cuffs of the ITER window unit without the brazing to the disc, able to accept 63.5 mm effective aperture diamond windows. The first preliminary tests, performed with a low power IMPATT source at 140 GHz showed the capability of a direct detection system to successfully work at powers several orders of magnitude smaller than what we would expect in a real life scenario. Additional high power tests in the presence of a cracked diamond will be soon performed.

Fig.3 Copper Cuffs test bench CATIA model

Pressure

Recent development has led to Pirani type micro sensors, with dimension in the order of few millimeters, capable of measuring pressures from 10^3 mbar to 10^{-6} mbar [15]. This kind of devices can be embedded inside the outer ring of the window assembly and can be easily substituted in case of failure given their cheap price and fast production.

IV. Implementation

In the original design of the windows assembly four generic cylindrical diagnostic ports are present. In the new design, these ports have been substituted by dedicated diagnostics subassemblies including all the aforementioned devices. In order to ensure reliability, redundant approach has been followed, implementing two independent iteration of each diagnostic on each window assembly. Symmetrically disposed on the cooling-diagnostics ring of the window assembly, the tritium, arc and pressure monitoring have been positioned on the same subassembly, while the horn antennas are inserted perpendicularly (Fig.4).

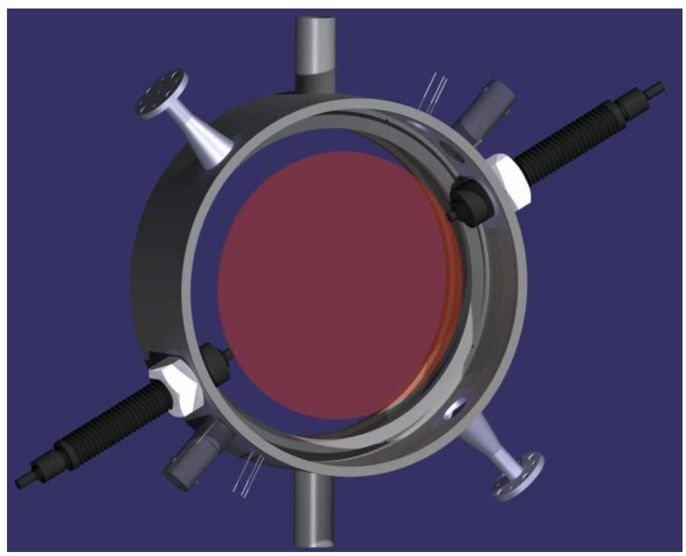

Fig.4 CATIA model of the modified cooling-diagnostic ring with added the horn antennas and the MW/arc/ pressure subassembly

The devices present on the diagnostics model mimic real life commercially available devices in standard sizes: the vacuum feedthrough is designed over M10 screws dimensions, the pressure chip is a standard size TO-5 chip package and the diamond detector (chosen as the best option after tradeoffs assessments) present a BNC compatible interface. Miniaturization is necessary, considering the tight spaces present in the current design. For the microwaves detection system, it has been necessary to design custom horn antennas, shorter than the commercially available ones. The smooth-walled, circular horn antennas connect to a standard G-band (140-220 GHz) WR-5 waveguide. The horn has been simulated via CST MicroWave Studio software, showing gains in the order of 20 dB (Fig.5).

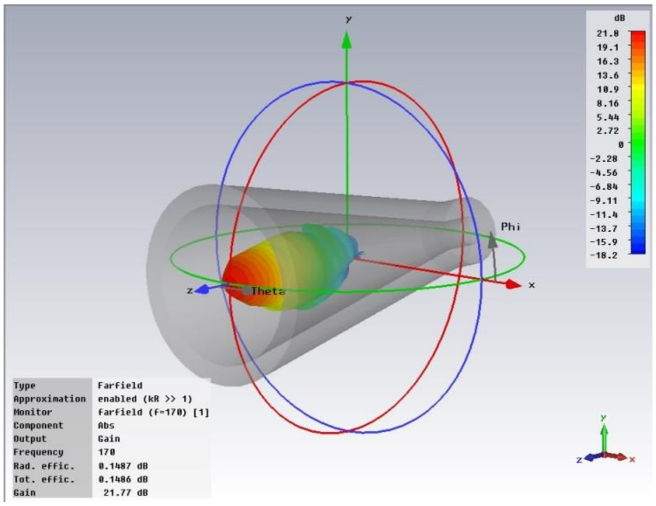

Fig.5 MW Studio simulation of the customized horn antenna gain

Preliminary tests on the customized horn antennas reveal wave collecting performances on par with commercial references (Fig.6). It is worth to be noted that while the commercial horn present a corrugated internal profile, the modified custom horns have smooth walls for manufacturing reasons. The setup we used to test the antennas was composed by an ELVA IMPATT -6/140 @ 140 GHz source coupled to a frequency sweeper and a network analyzer, both from HP. The detector was a Schottky barrier diode. The detector was calibrated before the test by directly coupling the source with the IMPATT diode through a variable attenuator.

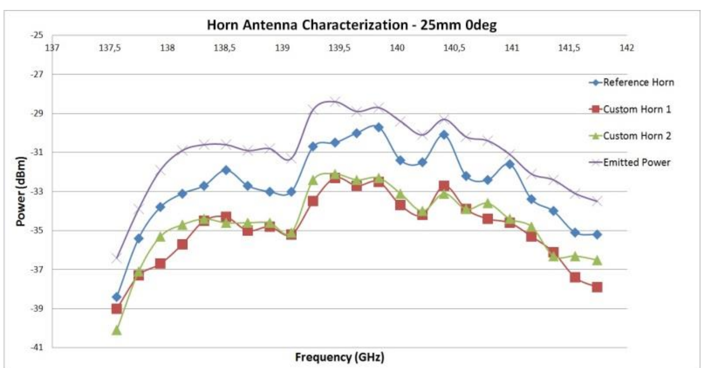

Fig.6 Comparison between the emitted power (purple crosses), the commercial horn (blue circles) and the two customized horn antennas (green triangles and red squares)

V. Conclusions

Tritium and arc detection are the most critical diagnostics, since electrical breakdowns and tritium leakages pose an immediate threat to the surround equipment and personnel. The other two diagnostics are meant more to monitor the integrity of the windows assembly. The data coming from multiple diagnostics can be combined through the diagnostics system to pinpoint the problem and its consequences with accuracy. The design followed a redundant approach, in order to provide continuous operation in case of failure of one of the elements, with the chosen devices promoting low volume occupation and reliability. The first test on the microwave custom designed horns revealed how their performances are similar to those found on commercially available, bigger solutions, and upcoming high power test will eventually confirm the value of the concept proposed.

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VI. References

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