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140-GHz Test Chamber for stray electron cyclotron radiation

Introduction

For the Wendelstein 7-X (W7-X) stellarator, ten 140-GHz gyrotron generators are being developed with an output power of 1 MW each. These generators are capable of continuous operation for up to 30 minutes. Their output frequency corresponds to the second harmonic of the electron cyclotron frequency at a magnetic field of 2.5 T.

Since the launched microwave power is dependent upon the plasma parameters and the heating scheme envisaged, the power is not completely absorbed in the first pass through the plasma. As a result, a microwave background level with a power flux density of up to 100 kW/m² can build up.

This high flux level could be critical for certain in-vessel components in particular because of the expected long-pulse operation of W7-X. Depending on the absorptivity and the heat capacity of the materials used for these components, they might either be destroyed or pollute the vacuum due to outgassing.

Thus, it is mandatory to test components such as valves, windows, gaskets, and in general all widely used materials to see if they are microwave resistant at the expected microwave power flux densities. For this reason a test chamber was constructed to generate a radiation density of the above-mentioned order of magnitude [1]. The chamber is operated by a dedicated 140-GHz gyrotron and features standard diagnostic ports so that planned diagnostic systems can be systematically examined before being assembled in W-7X.

Estimation of radiation density

The expected power flux density in W-7X can be estimated from a power balance, taking into account the three main loss channels: absorption by the plasma (first pass and on average), absorption by the plasma vessel walls, and loss of radiation through ports and windows [1, 2].

In the limiting case of no plasma absorption and 100% wall reflection, the windows are the only loss channel, and radiation density is calculated to reach 330 kW/m². Under more realistic assumptions of 60% absorption on the first pass through the plasma, with 5% wall absorption and 10% average plasma absorption, the radiation density approaches 90 kW/m². This result was experimentally verified by measurements conducted in the former W7-AS stellarator using special detectors described below [4].

Geometry of test chamber

To get reliable results from the planned tests, the most important preconditions are homogeneity and isotropy of the radiation inside the chamber. Both are strongly dependent on the proper choice of the launching geometry and the shape of the stray radiation test chamber (Fig. 1).

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Fig. 1. Stray radiation test chamber, l = 2.20 m, d = 1.5 m.

The dimensions of the vessel were chosen to be large compared to both the wavelength (2.1 mm) and the size of the test objects to avoid major disturbances of the radiation field (which is affected by the interference pattern of the inserted components), and thus the power flux inside the chamber.

A Gaussian microwave beam is launched and divided into two beam components by a flat mirror arrangement, generating two beams which propagate along the cylindrical chamber in the form of a screw (Fig. 2).

The radiation therefore does not reach directly to the central part of the chamber where the test objects will later be mounted. It is instead spread out in a screw-like pattern in the peripheral area. The intention is to make use of the fact that the vacuum vessel wall has a non-ideal surface so that each wall reflection is connected with random wave scattering, illuminating the chamber's central part from all directions in a uniform way.

It is important to consider the polarization of the radiation as well. Complete isotropization is the goal. Multiple reflections, each rotating the polarization according to the laws of reflection, lead to different ray directions with different polarization states adding up to a fully isotropic field in the central part of the test chamber.

Measurement of radiation density

The most important parameter to be controlled when operating the test chamber is the power flux density. To get reliable information over a wide range of power levels, different methods of measurement are used. Under high-power test conditions, multimode detectors were used to monitor power levels of the order of several tens of kilowatts per square meter.

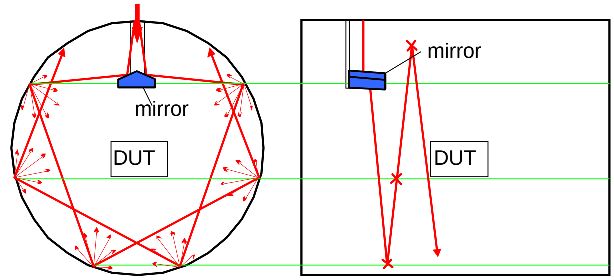

Fig. 2. Principle of chamber illumination with ray reflection and scattering. DUT = device under test.

All measurements to characterize the field distribution inside the chamber have been conducted at low power levels using an extended interaction oscillator (EIO) with an output power of 10 W to simplify operation.

Directional measurements

To measure the field geometry in the low-power operating mode, we installed a simple microwave direct-detection system that can measure the power flux with high spatial and angular resolution. During mechanical radial and angular scans of the system, data on position and power level are stored.

The measurements were done on two different ports of the test chamber, one located on the side to allow for a radial scan, the other at the end flange to allow for a scan along the axis of the cylindrical vessel. In both arrangements the central volume of the chamber was carefully explored, since it is of particular interest for later applications. The results are shown in Fig. 3. The radiation power flux density is given in terms of detector diode voltage with respect to the distance to the port used (x-axis) and the orientation angle of the detector (y-axis, 0° looking up, counterclockwise). The upper diagram was obtained by moving the detector along the diameter of the chamber and the lower by moving it along the axis. In the first case, the density plot shows four maxima of radiation flux, which combine into two (taking into account only the radial dependency). These are located left and right in the outer areas of the vessel, which can be reached by the screw-like rotating direct radiation that results from the geometry shown in Fig. 2.

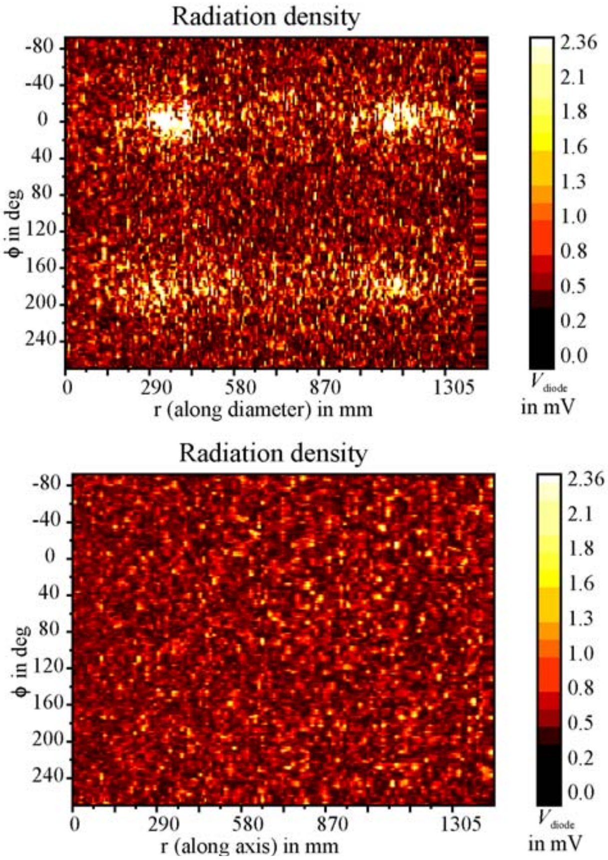

Fig. 3. Radiation density in the test chamber measured along a diameter (top) and along the axis (bottom).

A different situation obtains on the axial scan, which covers only positions that receive indirect radiation such that an isotropic and homogeneous radiation distribution is expected. Expectations are confirmed by the measurements given in the lower diagram of Fig. 3, thus demonstrating the applicability of the launching concept. It is of experimental and practical importance that a smooth and uniform flux distribution could be reached without any additional tools such as mechanically driven mode stirrers.

In addition to power measurements with the microwave detectors, the surface temperature of an absorbing sphere mounted inside the chamber was monitored with an IR camera and thermocouples in the sphere; these measurements confirmed the homogeneity of the radiation in the center of the test chamber. The total power throughput of the water-cooled test chamber was checked using calorimetry.

Multimode detectors

To determine the absolute power density in the high-power operating mode, multimode detectors, so-called sniffer probes, have been developed to be insensitive to the polarization of the radiation [3]. An oversized waveguide couples to the radiation field. About 400 modes can be excited at 140 GHz. It feeds a highly reflecting spherical cavity, 40 cm in diameter, in which the polarization is randomized by multiple reflections. A calibrated (monomode) detector diode located at a randomly chosen point on the sphere can then be used to measure the local power.

A typical situation in high-power operation mode is shown in Fig. 4. Because the gyrotron is not capable of pure cw operation, it is pulsed with a duty cycle of 1:10. The power pulses can be resolved by the sniffer probes and are shown in the diagram. The time-averaged irradiation power level is 27.7 kW/m^2.

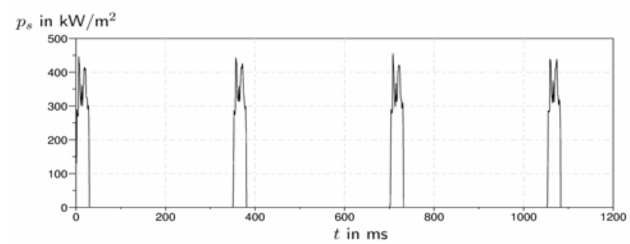

Fig. 4. Pulses from the gyrotron (sniffer probe).

First material tests

Under these conditions, the first material tests have been conducted. We decided to test three vacuum sealing O-rings, one made of conventional Viton, the others of replacement materials containing a smaller fraction of carbon to reduce the microwave absorptivity.

The rings were irradiated with 36 pulses of the gyrotron for 11 s. The behavior was recorded with an IR camera. Example results are given in Fig. 5. While the outer Viton ring was destroyed completely, the inner two ones of lower absorption could withstand this radiation level; they became hotter but maintained their integrity.

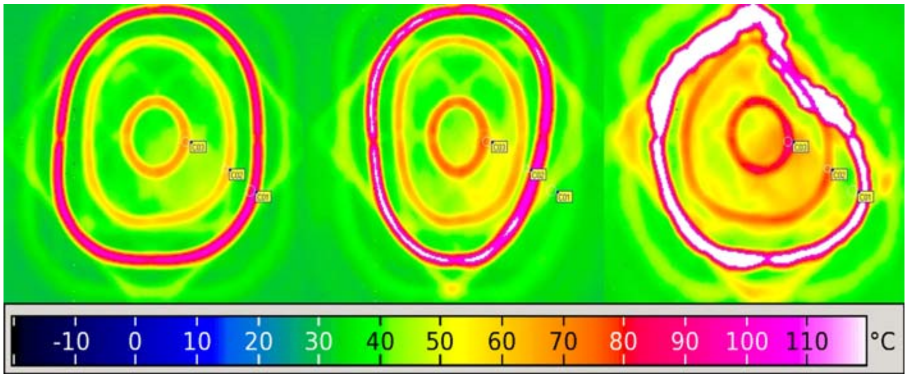

Fig. 5. Three different vacuum sealing O-rings during high-power irradiation tests. After 11 seconds at 27.7 kW/m², the Viton ring (at right) was destroyed.

Outlook

Following this extensive characterization of the radiation field and absolute measurements of the power flux density, the material test chamber is ready for routine operation. In the first major test campaign the ECRH launcher developed for the W7-X device will be investigated. It is planned to operate the chamber in a later phase with a 1-MW cw gyrotron to reach even higher power fluxes.

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