Distribution of the ECRH stray radiation in fusion devices

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Abstract
A new diagnostic for the ECRH stray radiation distribution was installed at the W7-AS Stellarator. The measurements were used to benchmark a newly developed model, which calculates the ECRH stray radiation distribution in fusion devices.

Introduction:

For fusion devices with high power long pulse or cw electron cyclotron resonance heating (ECRH) systems the danger of damages by the non absorbed ECRH-radiation arises. Two kinds of scenarios should be taken into account. First, damage by direct irradiation of the non-absorbed microwave beam, which causes a local heat loading of the spot size. Therefore all parts which can be hit by the beam should be adequately armoured. The beam trajectory can be calculated by ray tracing codes and is not the content of this paper. Second, after multiple reflections, a more less isotropic background level of ECRH-stray radiation is established in the vacuum chamber, which can interfere with and damage microwave sensitive diagnostics. Further, in long pulse or cw operation non-cooled microwave absorbing materials can be thermally damaged. To calculate this kind of radiation a multi-resonator model was developed.

Model

Let us start with a simple estimation of the radiation level in the case of an oversized resonator. We assume that the radiation is homogeneous, isotropic and isotropically polarised. Therefore the radiation intensity can be described by power flux density in the dimension of W/m^2. The power balance of the input power and the lost power defines the radiation level in such a resonator.

$$P_{in} = P_{abs,plasma} + P_{abs,wall} + P_{loss,window}$$

The input power is the non-absorbed ECRH-power. The sum over the radiation losses by absorption in the plasma at the walls and the losses through any hole in the chamber represents the loss power. The relative absorption is averaged over the angular distribution and polarisation of the radiation. The power balance can the be reformulated to:

$$P_{in} = p < \alpha > A_{EC-resonance} + p < \eta > A_{wall} + pA_{loss,window}$$

$$p = \frac{P_{in}}{< \alpha > A_{EC-resonance} + < \eta > A_{wall} + A_{loss,window}}$$

Where p is the isotropic power flux density, $<\alpha>$ is the averaged plasma absorption and $<\eta>$ is the averaged wall absorption. *A* is the area of the walls , windows and the EC-resonance in the plasma. For the last, its area has to be taken twice since the absorption can take place for low field side radiation as well as for high field side radiation.

This simple ansatz does not take into account the geometrical structure of the resonator. The only inputs are the size and the absorption of the resonator surfaces and the size of the holes. This, of course, is not sufficiently precise to calculate the radiation distribution in a more complicated structure like a torus and its ports.

Therefore this model is extended to the so-called multi-resonator (MR) model. Here the torus is assumed to consist of a number of resonators. In each resonator the assumption of the single resonator model above are fulfilled. But now there are connections to the neighbour resonators. The area of the connection and the name of the connected resonator determine them. Such a resonator for example can be a torus segment or a flange.

In this description the geometrical structure of the torus is reduced to its topology. This means that it is only taken into account which resonators (torus module, flange etc.) are connected with each other.

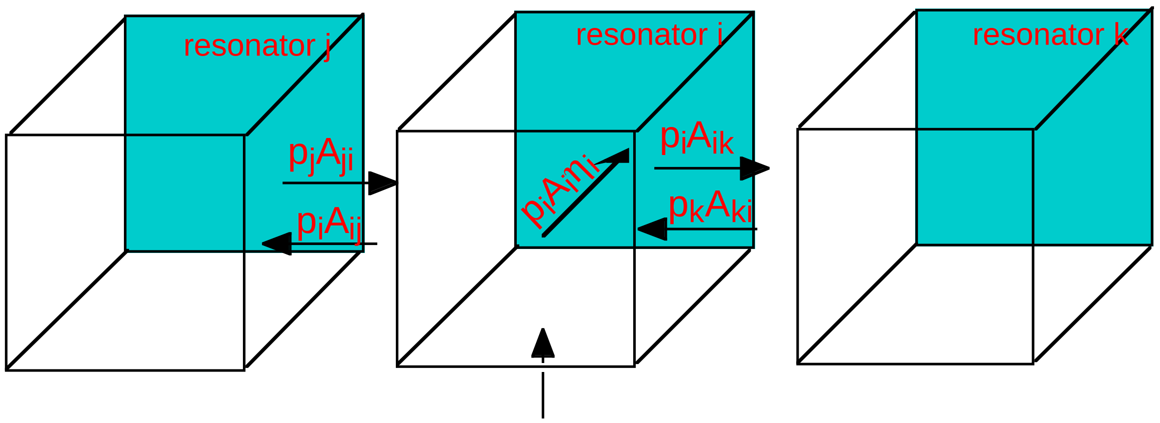

Fig. 1: Scheme of the ulti-resonator model.

The power balance is then:

$$P_{nonabs.ECRH} + \sum_{neighbour\ resonator\ j} p_j A_{ji} = \sum_{neighbour\ resonator\ j} p_i A_{ij} + \sum_{absorbing\ surfaces} p_i A_n \eta_n$$

On the left side there is the input power, which is the non-absorbed ECRH-radiation and the radiation coming from the neighbour resonators. At the right side there are the power losses by wall and plasma absorption and the power losses through the windows and through the connection surfaces to the neighbour resonators. What we get is a system of coupled equations for the radiation power flux density in each resonator. This is solved numerically.

$$p_i = \frac{P_{nonabs.ECRH} + \sum_{neighbour\ resonator\ j} p_j A_{ji}}{\sum_{neighbour\ resonator\ j} A_{ij} + \sum_{surface\ n} A_n \eta_n}$$

Further inputs are: The averaged relative microwave absorption of the different materials and the averaged plasma absorption. Both are represented by sum over $A_n \eta_n$.

Application and comparison with experiments.

The model was originally developed to calculate the ECRH stray radiation level of the Wendelstein7-X Stellarator, which is under construction now. It will have a 10 MW cw ECRH system. There are ECRH scenarios planed, where up to 2.5 MW ECRH stray radiation is expected for cw operation. To benchmark the code, measurements at the predecessor experiment Wendelstein7-AS have been performed. A further benchmark was performed with stray radiation measurement at the FTU-Tokamak [1]. In the experiments the microwave power density is measured at different positions at the torus with wide angle antenna characteristics - so called sniffer probes [1] - in order to collect all radiation approaching the probing surface independent on their propagation angle and polarisation.

The main chamber of Wendelstein7-AS consist of 10 half modules which are represented by the first 10 cells. The other cells represent the largest ports and some specific small ports where the stray radiation level is of particular interest. All in all the Wendelstein7-AS is modelled by 40 cells. In contrast to the FTU-Tokamak the Stellarator has a lot of in-vessel components like divertor elements, diagnostic, ICRF-antennas and ECRH-launch mirrors, which are more difficult to model. On the other hand the vacuum chamber is more than twice as large as the plasma, more over due to the toroidal variation of the magnetic field the EC-resonance layer is rather small compared to the wall surface. Therefore the assumption of an isotropic stray radiation should be fulfilled even in the presence of a well absorbing EC-resonance layer.

Four sniffer probes were located at different positions inside the torus. Probe 1 positioned directly into the ECRH-launch module, sniffer 2 measures the radiation inside a flange of the ECRH-module, sniffer 3 is located at a distance of 108°toroidal angle or 2.8 m from the ECRH-launch and finally sniffer probe 4 is located far away at the opposite ECRH-module ($\Delta\phi$=199°, Δl=6.9m).

First the radiation distribution in an empty plasma chamber was investigated. Especially before the plasma start up high non-absorbed ECRH-power levels can arise. Here near the ECRH launch power levels of up to 80 kW/cm^2 were measured at with a total ECRH power of 500 kW as shown in Fig. 2. The radiation at the probe 3 is damped by about 10 dB. The radiation in the shadow of a long flange (Probe 2) is also damped by a factor 4. This situation was simulated with the multi-resonator model. The radiation level was overestimated by an order of magnitude if only the surface of the pure vacuum chamber plus the divertor modules is taken into account. In addition, the large number of in-vessel components and windows has to be somehow modelled. Best agreement with the experimental data was found when the average wall absorption was set to about 30% (see Fig.2). Similar results were achieved in the case of a plasma density above the cut-off density.

When the plasma is established, the amount of non absorbed radiation is strongly reduced, due to the high X-mode single pass absorption with is usually 99%. Further, the damping of the rest radiation is increased by the large EC-surface. Except near the ECRH launch, the stray radiation levels are below 1 kW/m^2. The situation for plasma start-up, absorbing plasma and when the cutoff density is reached is illustrated in Fig. 3. It is remarkable that the stray radiation rises just before the critical density is reached, since due to refraction the single pass absorption is reduced even before.

Conclusions

ECRH stray-radiation at W7-AS reaches up to 100 kW/m^2 near the EC RH-launch in the plasma start-up or in operation above the cutoff density. For ECRH with a well absorbing EC-resonance the stray radiation is negligible. The MR-model was benchmarked with the experimental data for different situations. Now concrete predictions on the radiation level and distribution at W7-X are available. In addition the sniffer probes have demonstrated their potential as an interlock diagnostic to prevent damages due direct ECRH irradiation. Further they can be used to detect the mode purity of the injected ECRH beam.

References:

[1] F. Gandini, et al., *"The detection of non-absorbed millimeterwave power during EC-heating and current drive"* ,Fusion Eng. and Design, to be published.

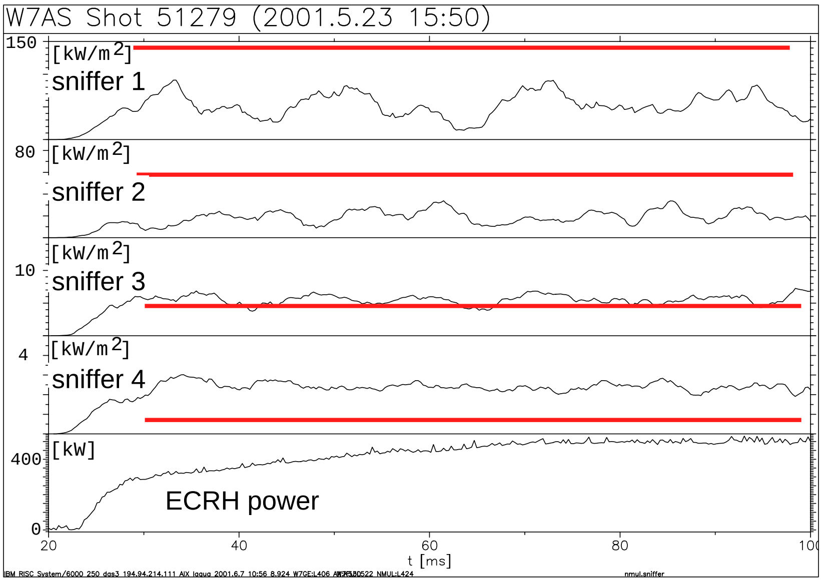

Fig. 2: From the top: stray radiation measured by sniffer probe 1,2,3,4 for 140 GHz ECRH injected in the empty W7-AS vacuum chamber. The bottom signal is the ECRH power. The signals were compared with the results of the MR-model (horizontal bars).

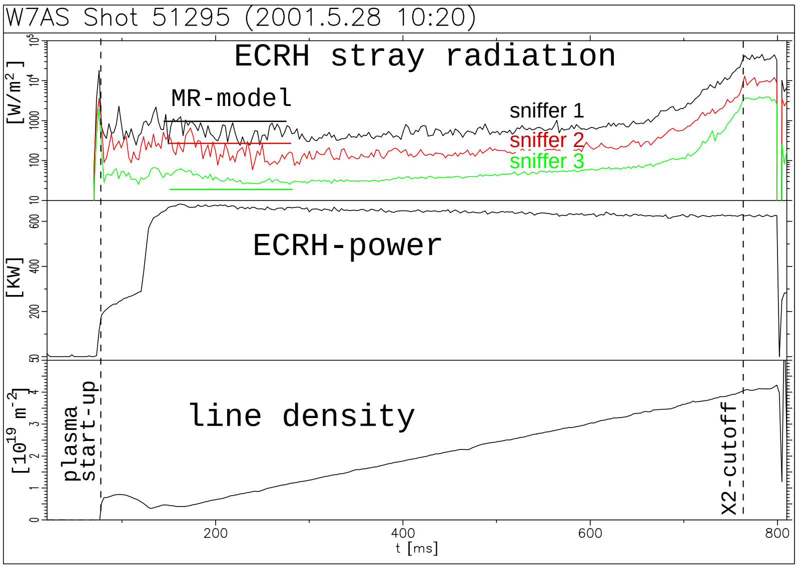

Fig. 3: Development of the stray radiation in a discharge, when the plasma density was risen up to above the X2-cutoff. The horizontal bars are results of the MR-model using an average plasma absorption of 50% (X2-mode and O2-mode) and a total stray radiation power of 2 kW.