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Design and concept validation of the new solid tungsten divertor for ASDEX Upgrade

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ABSTRACT

Div-III, a divertor with solid tungsten target tiles for ASDEX Upgrade is designed and tested and will be installed in 2013. It is a further step in exploring tungsten as material for plasma facing components. It avoids the restrictions of tungsten coatings on graphite and realizes an operation range up to 50 MJ energy removing capability in the outer divertor. In addition, it allows physics investigation such as erosion and deuterium retention as well as effects of castellation and target tilting. The design of the target itself and the attachment was optimized with FE-analysis and was intensively high heat tested up to a double overload. Cyclic tests reveal that the target and the attachment can be operated with the design load of 50 MJ without any damage. Even a twofold overload results in local recrystallization and minor cracks but the targets did not fail during operation. The redesign of the divertor structure was used to increase the conductance between the cryo-pump and the divertor region. The impact of the changed pumping efficiency was investigated with SOLPS/Eirene modeling. The modeling results are an indication for an easier access to lower SOL densities as expected for a higher pumping efficiency in the main chamber.

1. Introduction

ASDEX Upgrade (AUG) is a mid-size tokamak fusion experiment that was stepwise transformed from a carbon to a tungsten first wall experiment. Starting with the experimental campaign 2007 AUG was operated as a full tungsten experiment. It could be shown that tungsten and ITER like plasma performance are compatible as long as the central heating of the plasma is high enough to suppress tungsten accumulation in the core [1]. The transition from carbon to tungsten was realized by coating fine grain graphite with tungsten of different thickness [2].

The next step in the divertor improvement is the installation of a solid tungsten divertor made from powder metallurgy (PM) tungsten: This expands the operational range of ASDEX Upgrade. (i) It overcomes the problem of delamination of thick tungsten coatings in discharges with a peaked target heat load profile [2]. (ii) It avoids a frequent exchange of target plates with thin coatings that might be required due to the strong erosion in the outer divertor. (iii) It allows physics investigation such as erosion and deuterium retention of solid tungsten. In addition, effects of castellation and target tilting can be investigated under reactor like magnetic configurations.

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This paper presents the requirements and the principle design of the new divertor in Section 2. The concept validation as a combination of finite element (FE) analysis and high heat flux testing to ensure a reliable operation are presented in Section 3. The divertor modification is used to increase the pumping efficiency below the roof baffle and in the main chamber. The expected effects on the scrape-off layer (SOL) plasma parameters are modeled by SOLPS/Eirene and are presented in Section 4. Finally, a summary is given.

2. Status and design requirements

ASDEX Upgrade is equipped with an adiabatically loaded divertor consisting of 16 sections with 8 target tiles each. The operational limits are set by the thermal properties of the material and the connection to the cooling structure as indicated in Fig. 1. For AUG with a low heat transfer coefficient into the cooling structure, the operational limits are the energy limit and the energy impact. The energy impact is set by the tolerable surface temperature during the discharge whereas the energy limit is given by the equilibrium temperature of the bulk that is usually reached a few tens of seconds after the end of the discharge.

In the case of W coatings, the maximum tolerable surface temperature depends on the mismatch of thermal properties of the coating and the bulk material. High surface temperatures and temperature gradients result in mechanical strain at the interface

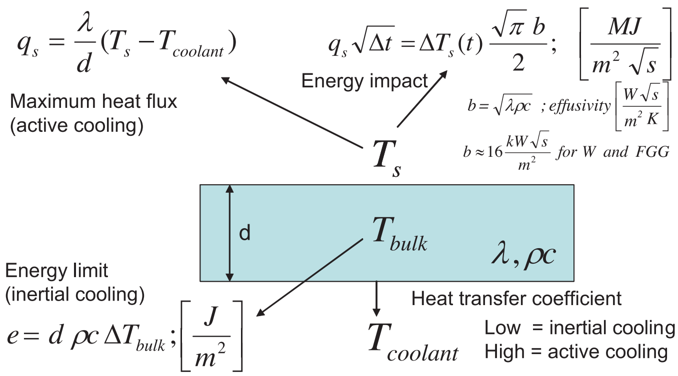

Fig. 1. Thermal simplified diagram of a divertor target with the energy impact, the maximum tolerated heat flux and the energy receiving capability as limiting figures.

between the bulk material and the coating and have caused the delamination of the 200 μm thick W-coating [2]. Uncoated graphite or solid tungsten allows a significantly higher surface temperature, i.e. energy impact. The energy receiving capability of coated and uncoated targets is comparable and depends on the heat capacity. It is about 50 MJ for the outer divertor of AUG with 3 cm thick graphite tiles or about 150 MJ plasma heating energy (details are discussed in Ref. [3]).

These figures have to be compared to typical values for applied heating energy of about 50 MJ in improved H-mode discharges or about 60 MJ in discharges with high P/R values, i.e. discharges with maximum heating power. The applied heating energy during plasma discharges is usually below the design limit of the target mainly because of the fact that at high heating powers plasma instabilities are dominating the plasma performance and the stability limit is reached often already at 7–10 MW heating power.

From these thermal requirements follow that a new divertor should have a higher heat impact capability compared to the W-coated divertor without the need to increase the energy receiving capability.

A design concept for a solid tungsten divertor was developed and tested in 2010. It consists of a sandwich structure that is compatible to the existing divertor support structure. The 30 mm thick sandwich is made from 15 mm thick tungsten in top of a 15 mm thick graphite adapter tile as presented in Ref. [3].

The concept to use flat solid tungsten plates with 15 mm thickness as target tiles was first tested in the high heat flux test facility GLADIS [4] and is now in operation in ASDEX Upgrade for 2 campaigns or about 1600 discharges [3].

Based on the successful test of the design concept the basic requirements for a new solid tungsten divertor Div-III were defined: (i) It should have the same energy and heat load receiving capability as a graphite divertor without tungsten coating. (ii) At present, the target plates are mounted to the support/cooling structure outside the vessel and the assembled divertor module is then installed into the torus. The use of solid tungsten tiles results in an increased weight of about 50 kg per divertor module. This requires tile assembly inside the vessel to keep the manual handling capability. (iii) The redesign of the divertor should be used to increase the pumping efficiency in the outer SOL by increasing the conductance between the divertor region and the cryo-pump, hopefully resulting in a decrease of the edge density. (iv) A reasonable price and the potential to be realized in the near future. The requirements (i)–(iii) are discussed more in detail in the following paragraphs.

(i) In between discharges, the divertor is cooled down to room temperature. During the discharge, the surface and the bulk temperature of the target tiles are permanently increasing, i.e.

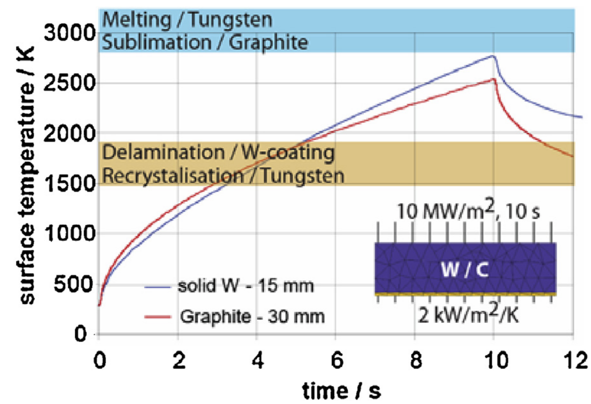

Fig. 2. Surface temperature evolution for a fine grain graphite and a solid tungsten target. The temperatures are calculated with a 2D-FEM code applying temperature dependent thermal parameters. Both targets are clamped with a graphite interlayer to the cooling structure realizing a weakly cooled target.

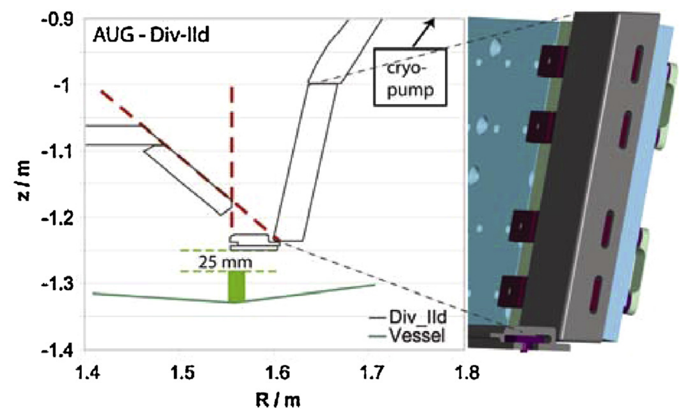

Fig. 3. Divertor geometry for the present Div-IIb divertor that has to be compared to the new Div-III geometry as shown in Fig. 4. Div-IId consists of 3 cm thick fine grain graphite plates clamped to a stainless steel cooling structure. The conductance below the outer divertor is low due to the small gab between divertor and vessel.

no equilibrium between heating and cooling is reached as typically for adiabatically loaded components. As a consequence, the surface temperature can increase up to the melting or sublimation temperature of the target material (Fig. 2). This large range of temperature evolution is not critical for graphite but means for tungsten that the temperature evolution starts with brittle material going through the temperature range where the material becomes ductile and a small fraction of the target thickness might reach temperatures above the limit for recrystallization of about 1500 K. This is accepted for ASDEX Upgrade because the total time with local target temperatures above 1300 K is about 50 s/a. The expected level of recrystallization is either negligible or limited to the first millimeters on top of the target. Even for the design case of 15 MW/m^2 for 10 s, the total time at temperatures above 1300 K is a few tens of seconds per year or about 10 shots. The maximum equilibrium temperature of the target that gives together with the heat capacity the energy receiving capability is specified with 1000 °C, i.e. it is well below the start temperature for recrystallization (see e.g. Ref. [5]).

(ii) The present concept of target tile fixing to the cooling structure is based on sliding blocks inside the target clamped by spring dishes to the support structure. This concept requires a pre assembly outside the torus. In addition, it weakens the material thickness in the regions of the cuts for the gliding blocks (see Fig. 3). The new clamping concept as shown in Fig. 4, uses claws