Progress in the Design and Development of a Test Divertor (TDU) for the Start of W7-X Operation

A Peacock[1], H Greuner[2], F. Hurd[1], J. Kißlinger[2], R König[3], B. Mendelevitch[2], R Stadler[2], F Schauer[3], R Tivey[1], J Tretter[2], C von Sehren[3], M. Ye[3]

[1]*European Commission, RTD-J4, assigned to the W7-X Project, Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany*
[2]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany*
[3]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, 17491 Greifswald, Germany*

Abstract

With the aim of starting plasma operation in 2014 the WENDELSTEIN 7-X (W7-X) Project has developed a scenario with an intermediate operational phase in which a reduced number of in-vessel components are installed prior to going to the fully equipped, full performance phase.
An important part of this scenario is the Test Divertor (TDU), an adiabatically cooled, reduced pulse length device that will allow machine operation over a comparable range of plasma configurations as the final long pulse high-heat flux (HHF) Divertor, which will be installed after two years operation of the TDU.
The design and development of the TDU has started by clearly defining the requirements of the TDU with regard to performance, material selection, geometry, interfaces to other components, diagnostic integration, installation requirements and tolerances and quality management. In fact, the whole TDU development will follow the procedures laid down for design and development of components within the W7-X project. This paper provides a description of the design and development of the TDU to date.

Topic: F
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Corresponding Author: Peacock
Alan.Peacock@ipp.mpg.de
Max-Planck-Institut für Plasmaphysik , EURATOM Association
Garching, Germany
Phone: +49 89 3299 1166

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Introduction

A new fusion experiment of the Stellarator type, Wendelstein 7-X, is currently being built at the Max Planck Institute for Plasma Physics, Greifswald. Over the coming years this experiment will be completed and start operation. The goal of this experiment is to prove the suitability of the Stellarator concept as a desirable alternative to the Tokamak for a future fusion power plant.

The W7-X machine has a divertor [1] consisting of 10 divertor units installed inside the vacuum vessel along the helical edge of the plasma contour, see Fig.1. This divertor system is used to control the energy and particle flow from the plasma confinement region at the plasma boundary. The components of the divertor that have to withstand high heat fluxes of power and particles are called the target plates. The target plates of the HHF divertor and the TDU consist of a series of target elements each with a 3D plasma facing surface.

Under stationary operation the heat radiated and conducted to the divertor requires that it is actively water cooled. Given the technically challenging nature of some of the HHF divertor components it has been decided not to install all of them at the start of W7-X operation but to start instead with an adiabatically cooled divertor known as the Test Divertor (TDU). This TDU will be replaced, after about two years of operation, with the actively cooled high heat flux (HHF) divertor.

The TDU therefore acts as the divertor which will be used during machine, plasma and diagnostic commissioning and for the initial development of a range of plasma configurations and modes of operation up to a significant fraction of the final machine performance but for shorter plasma pulse lengths.

To make the experience gained during the TDU phase as relevant as possible for the later HHF divertor phase, the geometry of the TDU follows as closely as possible the geometry of the HHF, especially the plasma facing surface. In addition the TDU will provide valuable information for the alignment of the divertor target surfaces to the magnetic confinement surfaces which will enable the optimum installation of the HHF divertor for long pulse operation.

Design specification of the TDU

An outline study was performed at the end of 2007 for the scenario with the intermediate phase of operation of the W7-X machine and a design concept for the TDU was developed and studied. The Project agreed a definition of the operating requirements of the TDU and these were expanded into a detailed list of requirements, outlining as comprehensively as possible the requirements of the TDU. The requirements related to plasma performance are given in Table 1. In addition the list of requirements also covers the following topics: Materials, interfaces, diagnostic integration, installation and tolerance requirements. These topics are expanded upon below. The conclusion of the design work for the TDU will be a design review and the list of requirements will be expanded into a full specification for the manufacture of the TDU.

Description of the TDU

The HHF divertor of W7-X is an open structure designed to achieve an effective power and particle exhaust for a wide range of operational magnetic parameters under steady state conditions. The amount, location and type of energy that will fall on the divertor units depends heavily on the power injected into the plasma, the magnetic configuration and the sharing of the incident energy between the various divertor units.

The TDU replicates many of the geometrical features, in particular the plasma facing surface, of the HHF divertor but uses fine grained graphite instead of Carbon-Carbon Fibre composite bonded to water cooled copper as the plasma facing material. This allows, in principle, the TDU to operate under the same range of operational magnetic

parameters as the HHF divertor and hence be used for the development of plasma scenarios for the HHF divertor. Viewed from the plasma side the proposed TDU looks very similar to the HHF divertor. A view from the front side of the TDU is given in Fig. 2.
The TDU divertor units must be able to withstand comparable levels of conducted and radiated power incident upon them from the plasma as the HHF divertor units. This can be achieved without significant investment and using low risk materials and technology but only for a limited pulse length.
Previous design reviews for the HHF divertor have identified 9 basic plasma configurations, which interact with the divertor target plates divertor over a toroidal length of 4.5 m [1]. The TDU, like the HHF divertor, consists of four distinct areas, see Fig.2. These are the horizontal target, the vertical target, the high Iota tail (for configurations with high Iota [1]) and the low heat flux region between the high Iota tail and the horizontal target. For each of these regions an adjustable support frame is foreseen onto which is mounted between 2 and 4 modules. A module consists of a stainless steel frame with graphite tiles mounted onto the front surface.
The graphite tiles of the TDU are monolithic pieces of graphite with a 3D machined front surface to reproduce the 3D target surface. The tiles have been designed to be as long as possible in the poloidal direction to maximise their heat capacity and to simplify instrumentation with thermocouples. The tiles are attached to the module frame with simple springs, see Fig.3. similar to those used in the W7-AS divertor, which has a similar design to the W7-X divertor but on a smaller scale [2,3]. This minimises the heat transfer to the module frame allowing the tiles to cool by radiation. Alloy 625 has been chosen because of its good high temperature properties, low conductivity and low permeability.

Materials and Testing

The materials used for the TDU are standard, readily available materials commonly found in many fusion experiments. The tiles are made of fine grain graphite, a low Z material, to minimize radiation losses in the plasma and are attached from the rear for the three main target areas to ensure that no holes are present in the tiles on the plasma facing surface. No special restrictions are placed on the Co content of the steels used as no operation with deuterium fuelling is foreseen in the TDU phase. Other requirements such as UHV vacuum compatibility, permeability limits and emissivity remain the same as for other components of the W7-X machine.
In spite of the standard nature of the target materials and technology, the geometry of the W7-X divertor is unique and it is intended to demonstrate that the modules work under the heat fluxes expected, prior to the final approval of the TDU design. Samples of a graphite material proposed for the TDU have already been successfully tested under the heat loads listed in Table 1 in the GLADIS facility [4]. In addition a prototype module is being built and will be tested at 8 MW/m^2 for 6 seconds, also in the GLADIS facility. The design of the prototype module is shown in Fig. 3.

Thermal Performance of the TDU

FEM analysis has been performed to demonstrate the development of the temperature of the TDU after repeated pulsing. The results of some these calculations are shown in Fig. 4. In this case with a 10 minute interval between pulses the surface temperature of the divertor reaches in excess of 1900ºC. To avoid the temperature

exceeding 1800ºC a duty cycle of greater than 10 minutes needs to be established, however, the specified value of 20 minutes for the inter-pulse period can be achieved, for full performance pulses. Further analysis has been performed for low power longer pulse operation.
These calculations include a radiation shield behind the divertor to avoid overheating of the thin pipes, intended for the later cooling of peripheral components, which are un-cooled during the TDU phase. Radiation cooling of the divertor results in radiation loads to the other un-cooled in-vessel components, such as the baffle, also shown in Fig 4. These components do not need to be protected as they withstand the temperatures reached.
Initial calculations indicate that thermal distortion of the module that lead to steps between adjacent tiles can be minimised to a fraction of the values obtained as a result of the installation tolerances; see Table 2. This is being further confirmed by full 3-D FEM analysis of the module that has the highest curvature.

Tolerance and installation requirements

The requirements for installation of the TDU inside the W7-X machine are as follows:

- The TDU must fit with the already designed and completed In-Vessel components; see [5]. This significantly limits the methods available for accessing the adjustment features.
- The TDU must have sufficient adjustment possibility to take into account the potential inaccuracy of the plasma vessel mounting brackets of up to +/- 6mm in all three directions
- The 10 individual units of the TDU must in addition be able to be aligned correctly to the plasma.
- The TDU units must be robust enough to withstand handling and being stood on.
- The plasma facing surface should be free, as far as possible, of steps between tiles. The requirements for the steps between tiles are given in Table 2.

These requirements have been met by the following measures. Adjustable feet have been implemented for the support frames of the TDU; these allow the accurate positioning of the TDU on initial installation. Additional adjustment of the individual units of the TDU is also possible after machine operation to compensate for errors in the position of the TDU with respect to the magnetic field. The exact position of the in-vessel components with respect to the magnetic field will only become known after initial operation. This adjustment possibility has been kept as simple as possible because of the limited man access for adjustment after operation, see Fig.4.
The attachment mechanism of the tiles to the module frames takes into account loading of the tiles from above, for example In-Vessel workers standing on the module. Nevertheless it is also foreseen to design protective covers to be placed above the modules after installation to evenly distribute the load and guarantee the integrity of the tiles.
The step in height between the individual tiles is also minimized by individually machining the tiles and then mounting them accurately onto the module frame using a template. The step between tiles on adjacent modules is minimised by mounting the

modules on a common support frame and adjustability is build into the region between adjacent support frames.
The ability to achieve the required tolerance on the steps between tiles will be tested on the same prototype that will be used for the GLADIS tests. This will also be tested between adjacent modules during assembly trials and it is planned to perform assembly trials of a lower and upper divertor unit in a wooden model of the plasma vessel before the final installation into the W7-X machine.

Conclusions

The design of the TDU is underway together with a parallel programme to demonstrate the ability of the designed components to meet the challenging requirements for this component. These are:

- the ability to withstand the heat loads and particle fluxes
- simple and quick to install
- adjustable after operation
- Plasma facing surfaces well aligned to magnetic field surfaces.

Much work is still to be done before the final planned installation of the main TDU components in 2012/3 but sufficient progress has been made to date to feel confident that the TDU can reach the requirements outlined in the list of requirements and be ready for installation by the deadlines specified.

References

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Figures

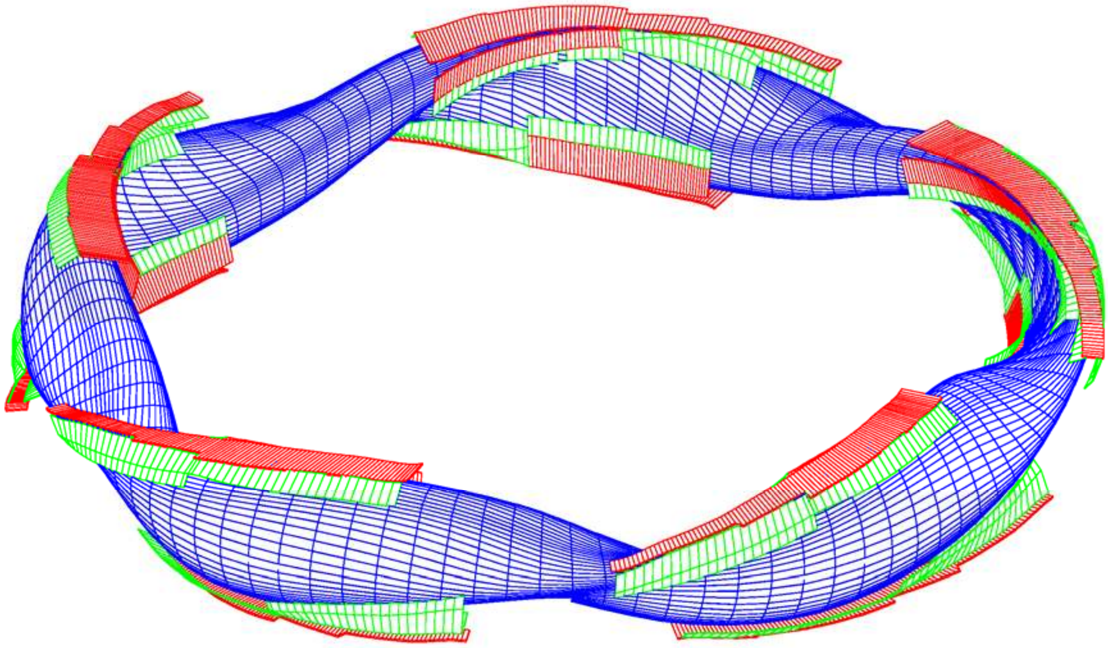
Figure 1: Schematic arrangement of divertor units along the magnetic configuration (the cross-section of the magnetic configuration strongly varies around the machine)

Figure 2: View of the front surface of the TDU showing a) Vertical target, b) Horizontal target, c) Low heat flux area, d) High Iota tail, surrounded by e) Baffle and f) Toroidal closure.

Figure 3: View of a TDU module a) from the rear side showing attachment features and b) from the front (plasma facing) side.

Figure 4: FEM analysis of the temperature development of the TDU under repeated pulsing.

Figure 5: Visualisation of the limited space for the adjustment of the TDU after installation of all the In-Vessel components



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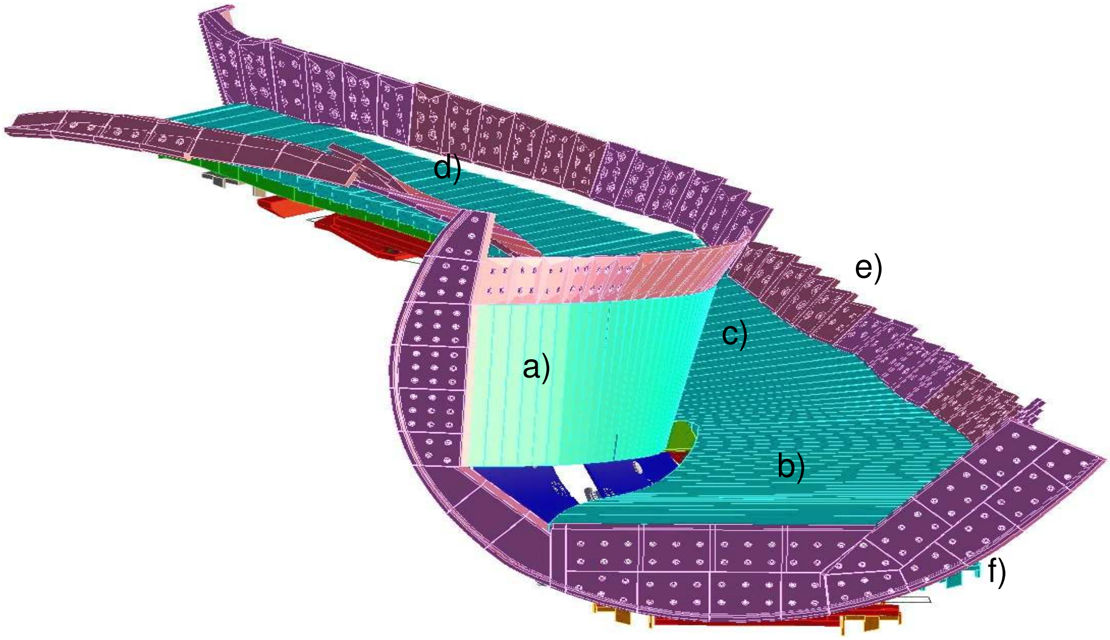

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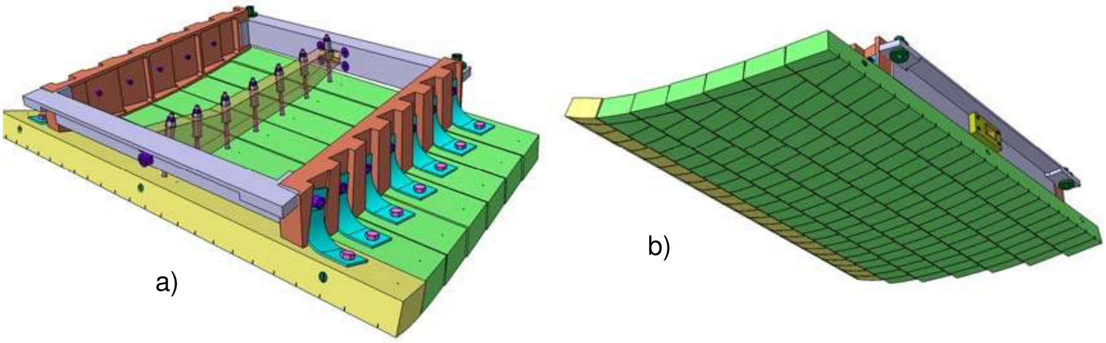

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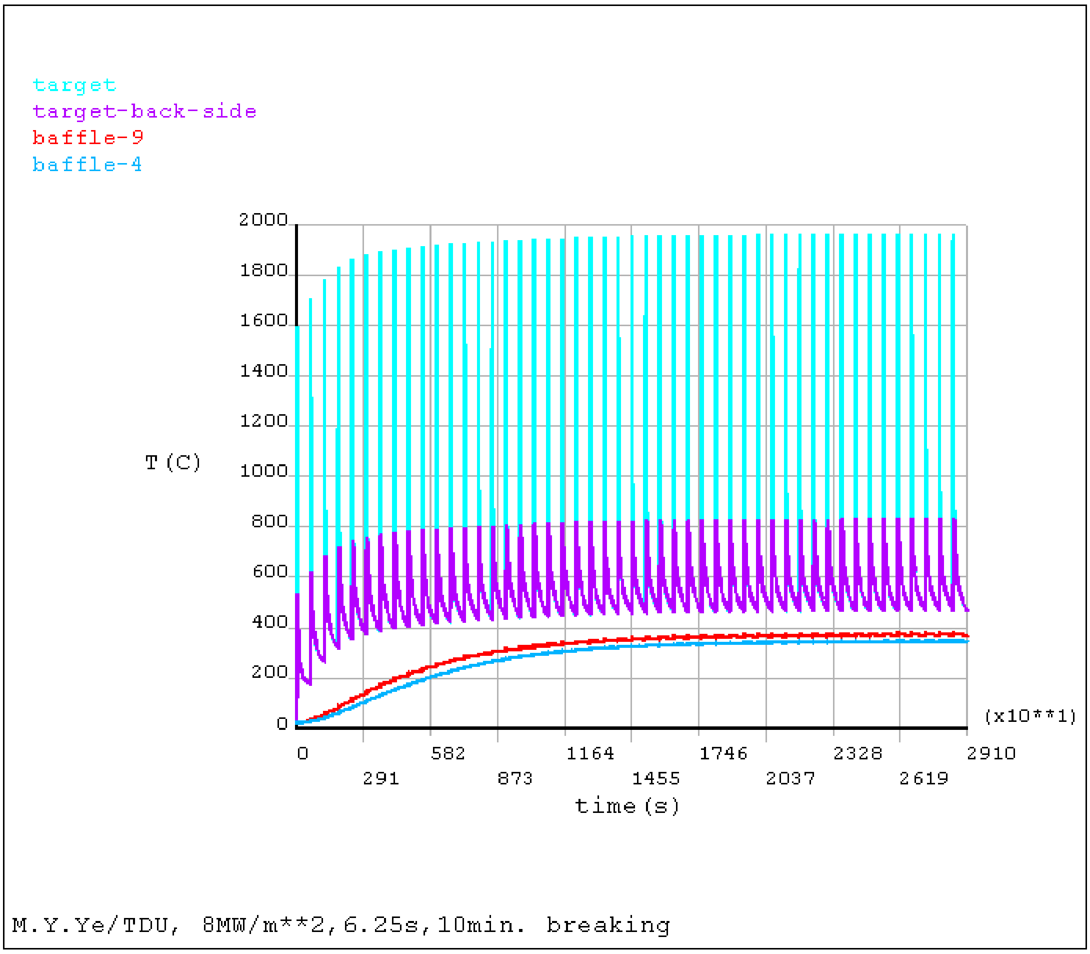

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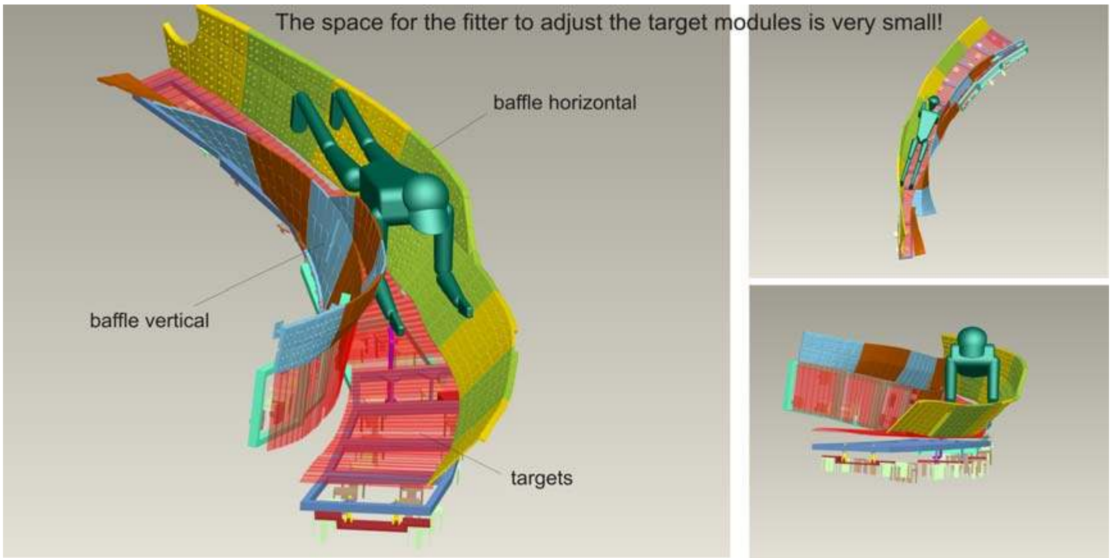

Figure 5 Visualisation of the limited space for the adjustment of the TDU after installation of all the In-Vessel components

Tables

Table 1: Operating Limits of the TDU

Table 2: Maximum step between adjacent components, within a divertor unit

	Operation with plasma
Plasma power max. [MW]	11
Maximum energy into divertor (10 units) [MJ]	50
Maximum energy into one divertor unit [MJ]	5
Surface local heat flux max. [MW/m^2]	8
Surface Temperature of Divertor [°C]	< 1800
Tmin. [°C]	10
Tmax.Structure [°C]	350
Pulse length [s]	40
Pulse repletion rate [min]	< 20

Table 1: Operating Limits of the TDU

Component	Maximum step between adjacent components
Target tiles	± 0.1mm
Target tiles (low heat flux area)	± 0.2mm
Target Modules	± 0.2mm

Table 2: Maximum step between adjacent components, within a divertor unit