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Scientific feedback from high heat flux actively cooled PFCs development, realization and first results in Tore Supra

A. Grosman*, P. Bayetti, C. Brosset, J. Bucalossi, J.J. Cordier, A. Durocher, F. Escourbiac, Ph. Ghendrih, D. Guilhem, J. Gunn, T. Loarer, M. Lipa, R. Mitteau, B. Pegourie, R. Reichle, J. Schlosser, E. Tsitrone, J.C. Vallet

Association Euratom-CEA sur la fusion, DSM/Département de Recherche sur la Fusion Contrôlée, CEA/Cadarache F-13108 Saint Paul Lez Durance Cedex, France

Abstract

The implementation of actively cooled high heat flux plasma facing components (PFCs) are one of the major ingredients required for operating the TORE SUPRA tokamak with very long pulses. A pioneering activity has been developed in this field from the very beginning of the device operation that is today culminating with the routine operation of an actively cooled toroidal pumped limiter (TPL) capable to sustain up to 10MW.m^{-2} of nominal convected heat flux. A technical feedback is given from the whole development up to the industrialization and focuses on a number of critical issues, such as bonding technology analysis, manufacture processes, repair processes, destructive and non destructive testing. The actual experience in Tore Supra allows to address the question of D retention on carbon walls. Redeposition on surfaces without plasma flux is suspected to cause the final "burial" of about the injected gas during long discharges.

JNM keywords : C0100 Carbon, F0800 Fusion Reactor Materials, H0400 Hydrogen and Hydrides (includes Deuterium and Deuterides), J0100 Joining (includes Welding, Brazing, Soldering), L0200 Limiter Materials, P0500 Plasma-Materials Interaction

PSI 16 keywords : Co-deposition, Deuterium inventory, Limiter, Tore Supra

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* Corresponding author address : A. Grosman, DRFC/SIPP, bat 506 CEA/Cadarache F-13108 Saint Paul Lez Durance Cedex, France

* Corresponding author e-mail : Andre.Grosman@cea.fr

1. Introduction

The steady state aspects of tokamaks discharges remains essentially a “terra incognita”. One of the major difficulties is that among the many time constants at stake, most of those involved in plasma wall interaction physical processes are difficult to assess and could likely be extremely long. Tore Supra (R=2.36 m, a=0.72m) is the first fusion experiment designed for long pulse operation with a high level of additional power (~20 MW, 30s then 1000s) [1], which addresses these points through integrated physics and technology solutions and this first applies to the plasma facing components (PFCs). For them, the full integration is a very demanding process, involving complex R&D, an industrial manufacturing route and specific implementation requirements for the system to be installed inside the plasma vessel. From the very beginning of the project, this required the implementation of high heat flux actively cooled plasma facing components. The first generation of components exhibited some weaknesses that were due essentially to the difficulties encountered in joining carbon to a metallic substrate [2] ; this was even more difficult when too complex designs have to be implemented [3]. A new project (so-called CIEL for Internal Components and Limiters in French) was launched to install a new generation of reliable high heat flux (HHF) Plasma Facing Components (PFCs), based on hardened copper alloy heat sink structures covered by a CFC armour. These have been developed in order to enable a large enough power exhaust capability. This resulted in a state of the art actively cooled high heat flux component, the so called finger element, which is able to handle up to 10 MW/m^2. A schematic representation is displayed in figure 1. In the frame of CIEL project, about 600 of such high performance parts have been manufactured to build the 7.6 m^2 Toroidal Pump Limiter (TPL) [4]. This assembly has been operated in Tore Supra since Spring 2002, participating to a new world record with the achievement of a 6min. long discharge, involving the injection more than 1GJ [5].

In spite of a well defined R&D programme, and a robust design [6], some difficulties occurred during the manufacturing phase, resulting in delivery delay. The experience gained is a unique input for the fusion community and is summarized in section 2. Moreover, the implementation of a fully actively cooled in-vessel, as the CIEL project also involved a full vessel coverage with actively cooled elements, yields access to the integrated physics of long discharges : this paper will stress in section 3, the progress made in understanding the deuterium retention in long discharges in conditions which are partly ITER relevant.

2) Technical feedback from CIEL realisation

The major technical issue that has to be solved is the assembly of a “plasma compatible” substrate to a heat sink which could provide both the heat exhaust through pressurized water and mechanical integrity. In Tore Supra, as in ITER, the former is carbon while the latter is a hardened copper alloy. It is important to also notice that this metal has to be linked to stainless steel which is the metal used for the cooling pipes.

The carbon material is a carbon-carbon fibre composite (CFC). The major difficulties for this kind of materials arise from the variability of the production from one batch to another or even during a single batch, since the production process is unable to achieve completely similar results.

The hardened copper alloy CuCrZr was rapidly preferred to the dispersion strengthened Glidcop essentially because its extremely low ductility preventing any welding. However, different companies producing CuCrZr do not elaborate the material in a similar way and the composition may differ from one to another. Welding tests were done, so as to assess the ability to minimize cracks within the seam weld. The scientific output of these investigations is still not completely clear and a significant R&D programme is thus still required.

As far as the carbon copper joining is concerned, OFHC copper is been used as an intermediate compliant layer. As brazing techniques induce thermal cycling incompatible with maintaining copper properties, active metal casting technique ($AMC^{®}$), developed by the Plansee company, was finally chosen, to ensure a very strong CFC-Cu mechanical attachment. The complete joining is a two phase process, creating the C/C-OFHC and the OFHC-CuCrZr interfaces in two successive separate steps. The first step consists of a laser treatment of the CFC tile surface to be bonded (machining of micro cone shaped holes), followed by Active Metal Casting ($AMC^{®}$) of a 2mm thick, soft copper compliant layer, onto the rear side of each CFC tile. The quality of the CFC/soft-copper joint homogeneity is then checked by X-ray radiography perpendicular to the tile surface, while the occurrence of eventual thin cracks in the CFC is now detected by lock-in thermography. The second step consists of EB (Electron Beam) welding of the AMC tiles in order to create a thermally conductive interface between the OFHC layer and the CuCrZr heat sink. The heat affected zone depends strongly on EB welding parameters. However the material properties change only locally (while the bulk material remains unchanged) and can therefore be restored (e.g. thermal conductivity), as far as possible, by an adequate heat treatment.

A major technical lesson from the experience gained with producing the limiter fingers is that the 5-year-long R&D programme carried out before manufacturing allowed us to gain confidence with in the validity of the various processes. Nevertheless, the production conditions for such elements do not allow us to draw quantitative conclusions about the risks of defects in each involved process. This is extremely problematic for systems which cannot be designed with wide enough margins (the lowest being about 40% for the TPL)and that rely on specific and not easily available materials, plus numerous and complex processes. Obviously, the number of processes should be minimised at least for those involving a non-negligible or non-assessed risk while a production involving many subcontractors will introduce additional risks linked with possible cumulative delays.

The industrialisation remains an essential step and its control will depend on the ability to fully specify the required product and consequently the capability of designing acceptance tests with well defined criteria. Many tests were achieved by the supplier during the manufacturing process. The X-ray test on every AMC tile was essential to qualify its attachment before welding. Nevertheless, the difficulties encountered during the manufacturing [7] again question the ultimate quality of the AMC bond. Lock-in thermography would permit ascertaining both the thermal and mechanical integrity of the bond before and after welding of tiles.

The so called SATIR test was essential as a final acceptance test for the whole element. The method is based on IR measurements of tile surface temperatures during a thermal transient produced by hot/cold water flowing in the heat sink cooling channel. This inspection method was introduced during former improvements to inner first wall components [8] and is the subject of continuous improvement [9]. The definition of an acceptance criterion led to extensive studies including the realisation of measurement on fingers with well defined defects.

The SATIR tests permitted detecting variability of the produced elements during the manufacturing ; decreased quality (measured from the production rejection rate by both the supplier and us) after the first batch production was unexpected. However, the acceptance test permitted a quantitative monitoring of the production. Good acceptance rate for single tiles resulted in some case to a rejection rate approaching 50%, due to the number of tiles (21) on each element. This could have impaired the whole production : the production of additional elements being in any case affected by the severe delays related to providing materials (especially for CFC). Consequently, a repair process proved to be a required development during manufacturing. The principle involved exchanging a faulty tile for a new one without affecting the other acceptable tiles. A specific welding procedure was found to be effective. It could be firmly validated by means of a HHF test [10], in good correlation with the SATIR test.

3) Preliminary scientific feedback from Tore Supra operation with actively cooled plasma facing components

The monitoring of high heat flux elements is mandatory, to serve the two aims of immediate safety (in view of the few seconds thermal time constant involved) as well as of in situ behaviour assessment. It is based on the observation of surface temperatures using infrared endoscopes and fibres which were developed within the CIEL project [11]. However, this monitoring is influenced by many parameters like additional thermal resistance in the structure or surface “dust and layers”. Their evolution in time complicates the thermal analysis and notably the transposition of surface temperatures to heat fluxes, which is the required information for the safety monitoring of actively cooled components, and the involved questions are developed in [12,13]. However, the experimental campaigns which have been carried out in Tore Supra since the complete upgrade of all plasma facing components, proved that the TPL allows reliable steady state operation at significant injected power (up to 9.5 MW peak, 6 minutes at 3 MW). A specificity is that the surface temperature remains constant (the thermal time constant being about 1s) at a relatively low temperature (about 540 K for the above quoted longest discharges) due to the low CFC thickness. Slightly higher temperature may be recorded on carbonaceous deposits but they also are constant. A simple 1D thermal calculation tool linked to the database has been developed and is used to allow flexible analysis of the ageing of the bond between the tile and the metallic cooling structure from the surface temperature measurement [12]. So far, no evidence of ageing has been observed after the three first years of operation. It gives confidence in the bonding technology used to manufacture the high heat flux components of Tore Supra.

If steady state heat exhaust is nearly achieved in Tore Supra, the remaining improvement concerning a complete enforcing of the adequate available technologies and operational limits, see e.g. [14], the particle control remains a major concern in view of ITER. This generally addresses two major issues. The first one is erosion, but can hardly be studied on a macroscopic scale in Tore Supra. The other one deals with hydrogenoid retention in a carbon dominated device. A major asset of the experiments in Tore Supra stems from the full active cooling of the plasma facing components, as it allows both to perform really long discharges, thus exceeding some first order limits (see hereafter), but also in conditions where the components surface temperature remains constant. This appears to considerably ease the interpretation of the experiments which are generally much more complex, if one should include surface temperature effects playing a prominent role in primary processes such as carbon chemical sputtering, or deuterium desorption.

A major finding from all the long discharges in Tore Supra, with duration exceeding 2 minutes is that a constant build up of the deuterium vessel inventory, independently of previous conditioning or discharge history [15]. One can relate this to a codeposition (C and D) mechanism. On shorter time constants (typically the first 100s), an additional loss term is recorded which is likely linked to implantation up to saturation on areas accessible to both ion and charge exchange neutral flux. This phenomenon is studied with very reliable particle balance based on barometric measurements [16] : it seems to be very robust, and depends only slightly on the gas fuelling method [17]. In the long discharges, for which the operational window is actually very narrow due to the low current drive capability now available, the injected fuelling rate amounts to about 2 10^{20} s^{-1}. From this, about half is finally pumped during the discharge, while the rest is “buried”. At the same time, the D recycling flux, deduced from the Langmuir probe sol density and temperature profiles (T_i being deduced to account for the recorded heat outflux), with the assumption of a 5% C carbon concentration in the edge, amount to about 2 $10^{22}s^{-1}$. Accordingly, the carbon flux onto the PFCs amounts to $10^{21}s^{-1}$… and a significant fraction of this flux is likely to be involved in the “D burial” (10^{20} s^{-1}) by codeposition. This can be partly understood if one takes into account the specific plasma wall interaction conditions.

The plasma edge parameters, that are recorded in such long discharges are characterised by a rather high electron temperature (about 60 eV with an e-folding length of about 0.08 m) and a low density (about 6 10^{18} m^{-3} with an e-folding length of about 0.05m). Another peculiarity of the Tore Supra plasma wall interaction scheme is that the magnetic field ripple is large enough to define a periodic structure (n=18, equal to the toroidal field coils number) for the plasma wetted area. As might be noticed on figure 2, the latter are surrounded by private zone where the plasma flux is negligible. To characterise the zone where erosion occurs compared to the one where deposition dominates, one relies on a very simple criterion, i. e. $\Lambda_{Crit} = Y_{D\rightarrow C} / (1 - Y_{C\rightarrow C})$, where Λ_{Crit} is the critical carbon concentration above which deposition dominates on erosion, $Y_{D\rightarrow C,}$ the carbon sputtering yield by deuterium, $Y_{C\rightarrow C}$ the carbon self sputtering yield. It is easily shown that Λ_{Crit} exceeds 5% as long as the temperature exceeds 30 eV , provided carbon is at least 4 times ionised. This criterion is then applied to the TPL surface where the heat flux measured by IR thermography and idealised to corresponds to heat deposition calculations based on a simple e folding length models is transposed to plasma edge parameters deduced from the Langmuir probe measurement as mentioned above. Particle fluxes, electron temperature and thus sputtering yields are calculated, which allows to check that the deposition rate concerns essentially the private zone, which in fact is very close to the main erosion and d recycling zone. Although the detailed physical mechanism could not determined up to now, one could envision that a significant fraction of carbon is redeposited in this region, while burying D. In fact the private zone is found at each Tore Supra vent to be covered with C deposits.

High D content would be expected in such deposits, which is not found experimentally [18]. In fact, it appears that most of these deposits, which have no good thermal contact to the actively cooled structure may reach high temperature during disruptions. This in turn can induce enormous desorption rates (severe disruptions allow to extract up to 10^{23}D, equivalent to a 1000s plasma burial fluence, and 1200 times more than what is desorbed at the end of a conventional discharge).

4) Conclusions

The routine operation of an actively cooled toroidal pumped limiter (TPL) capable of sustaining up to 10MW.m^{-2} of nominal convected heat flux appears as the achievement of a long lead development and industrialization program. Although ITER and Tore Supra HHF components designs are different, we believe that some general lessons learned from this experience do apply to ITER construction. This, in particular, applies to the extreme importance of developing the characterization and qualification of the whole element, including R&D but also prototype and preseries qualification, preparing in detail acceptability procedures (criteria, test facilities) and fallback issues (repair processes), so that the margins remain under control up to delivery.

If heat exhaust seems well controlled in Tore Supra, this is not the case for particle control as half of the injected flux remains buried within the vessel during long discharges. Even if, for such discharges in Tore Supra, the edge parameters are not fully ITER relevant, a major conclusion is that, even for conditions for which chemical sputtering is minimized, a significant fraction (about 30%) of the sputtered carbon participate to this D retention process, on non plasma affected zone of the limiter. An encouraging finding is that, on the long run, a process (likely sudden heat deposition during disruption) is able to desorb most of retained D in those adiabatic thin surface carbon layers.

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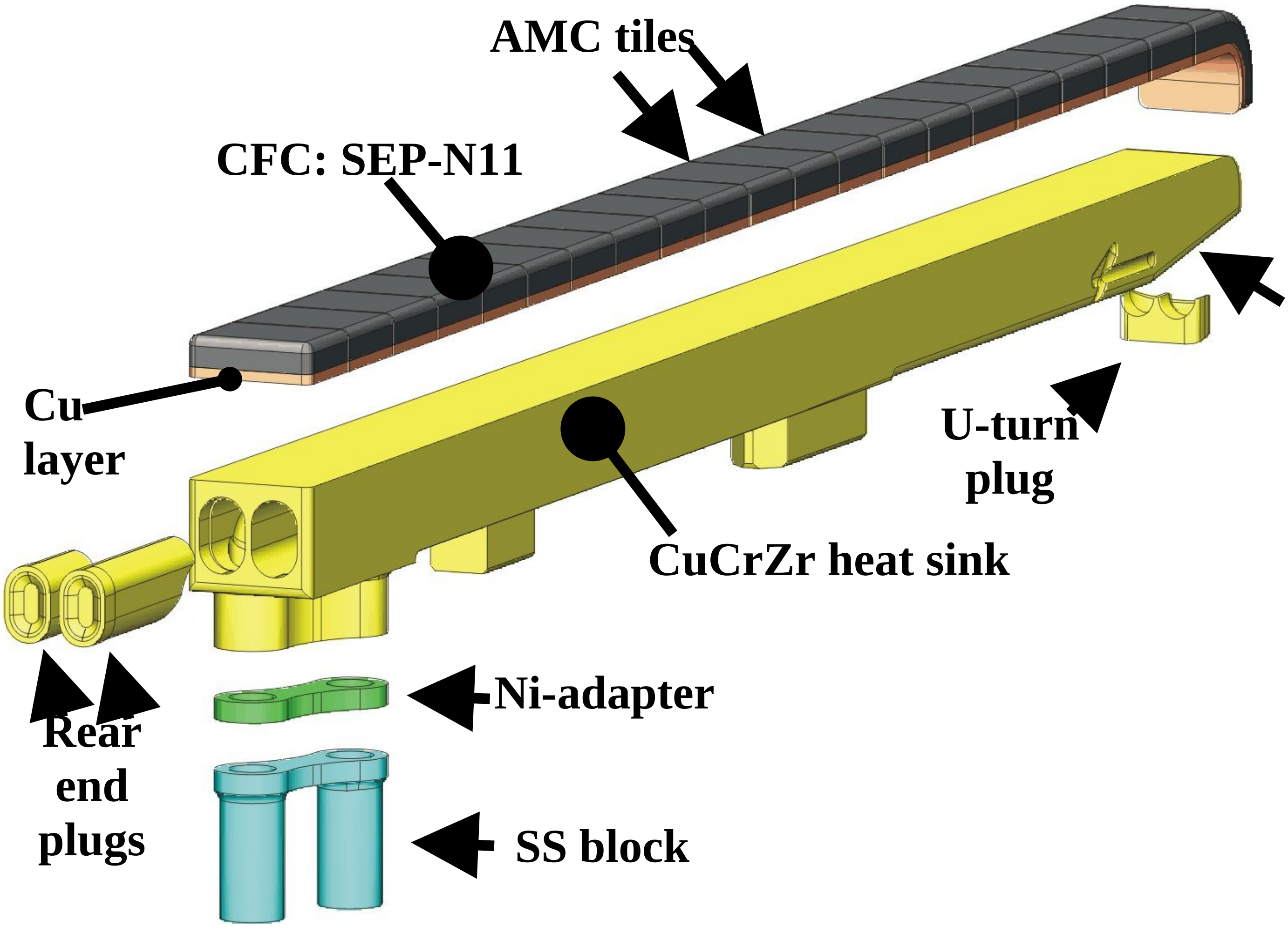
Figure Captions

Figure 1 : Break up view of the “finger” element of the Tore Supra toroidal pump limiter stressing the material assembly.

Figure 2 : Contour plot of the critical carbon concentration in the plasma (a), stemming from calculated plasma conditions involved in plasma wall interactions on the Tore Supra limiter. 1/18th is represented here, in toroidal and poloidal directions. (b) displays as an example the plasma electron flux onto this limiter section

Figure 1

DESCRIPTION OF THE ELEMENTARY



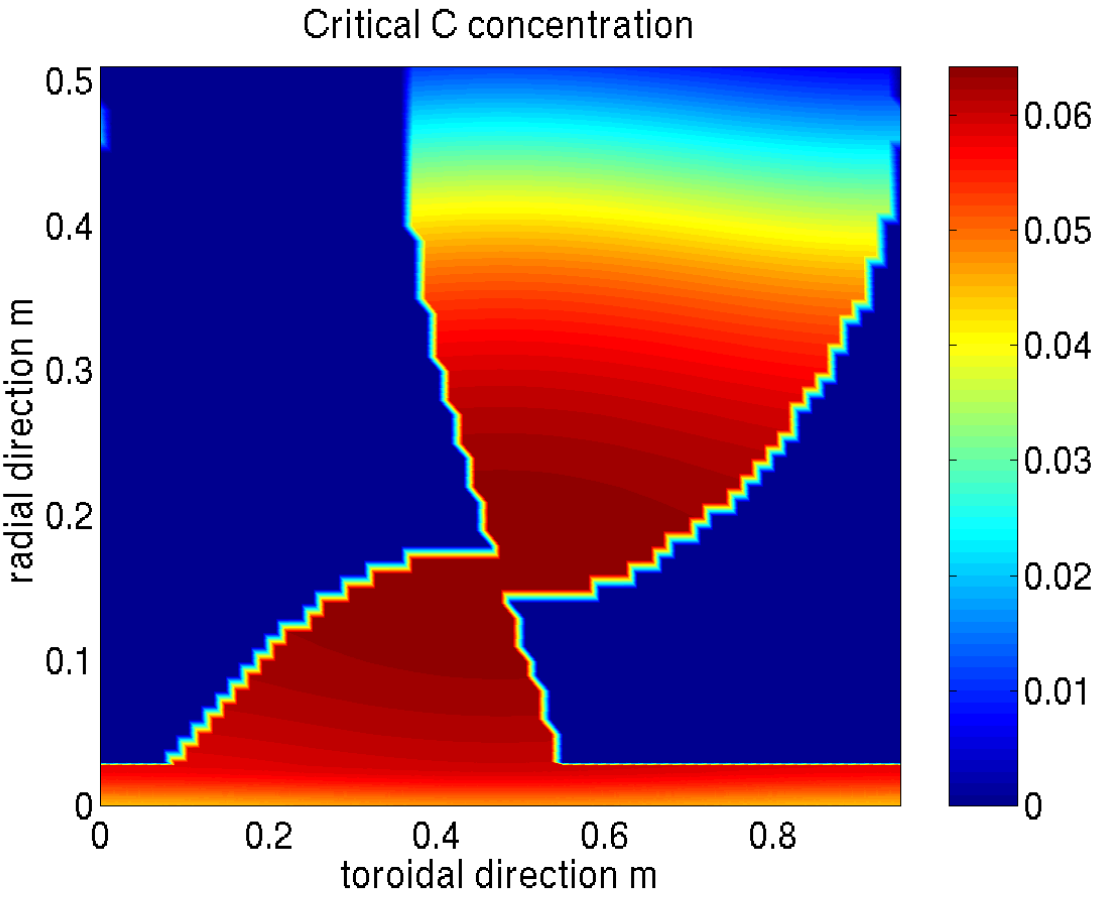

Critical C concentration
radial direction m
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
toroidal direction m
0.06
0.05
0.04
0.03
0.02
0.01
0

Figure 2a

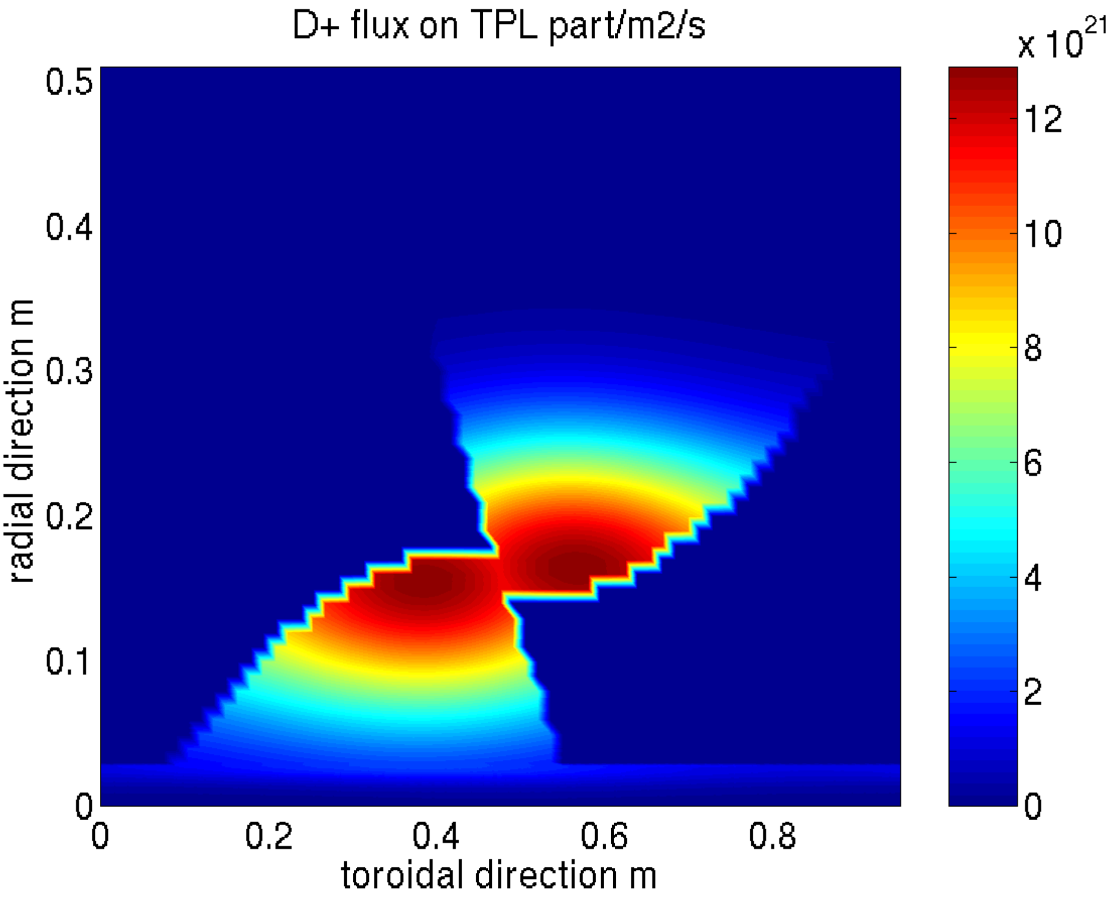

D+ flux on TPL part/m2/s
x 10^{21}
12
10
8
6
4
2
0
0.5
0.4
0.3
0.2
0.1
0
radial direction m
0
0.2
0.4
0.6
0.8
toroidal direction m

Figure 2b