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** See annex of F. Romanelli et al, "Overview of JET Results", (25th IAEA Fusion Energy Conference, St Petersburg, Russia (2014)).*

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ABSTRACT.
The ITER Organization has recently decided to install a full-tungsten (W) divertor from the start of operations. One of the key issues with such a strategy is the possibility of W melting and melt splashing during transients, which can lead to modifications of surface topology and which may lead to higher disruption frequency or compromise subsequent plasma operation. Although every effort will be made to avoid leading edges, ITER plasma stored energies are sufficient that transients can drive shallow melting on the top surfaces of components.

A new experiment has now been performed on JET-ILW in the ITER-Like Wall (ILW) environment, in which a deliberately misaligned W element (lamella) in the outer divertor has been used to perform controlled ELM transient melting experiments for the first time in a tokamak. This paper reports on the application of the 3D MEMOS code to modeling of these experiments. Input heat loads are obtained from experimental data, notably high resolution IR camera thermography. Importantly, the code indicates that that shielding by the evaporated tungsten prevents bulk melting between ELMs. Encouragingly, the simulations are also able to quantitatively reproduce the dimensions of the damaged area observed by high resolution photography after the first pulse in which melting was achieved.

3D MEMOS simulations on the consequences of multiple ELMs expected in ITER on damage of tungsten castellated armour have been performed for several scenarios of impact conditions specified by IO. Numerical simulations demonstrated that the **JxB** force caused by the thermo-emission current produces negligible melt layer displacement in comparison with the melt layer damaged produced by the tangential friction force of the impacting plasma.

1. INTRODUCTION

The ITER Organization (IO) has recently decided to install a full-tungsten (W) divertor from the start of operations [1]. One of the key issues with such a strategy is the possibility of W melting and melt splashing during transients, which can lead to modifications of surface topology [1,2] and which may lead to higher disruption frequency or compromise subsequent plasma operation. Although every effort will be made to avoid leading edges, ITER plasma stored energies are sufficient that transients can drive shallow melting on the top surfaces of plasma-facing components (PFC) [1].

Experiments designed to investigate plasma transient heat load damage of ITER-like W targets have traditionally been performed in QSPA plasma gun facilities [3], in which the transient plasma pulse pressure significantly exceeds the values attainable in tokamaks, including ITER, and the melt motion dynamics are determined by the tangential friction force of the impacting plasma. A new experiment has now been performed on JET in the new ITER-Like Wall (ILW) environment, in which a deliberately misaligned W element (lamella) in the outer divertor has been used to perform controlled ELM transient melting experiments for the first time in a tokamak [4-6]. The 3D MEMOS code [7] is applied to modelling of these experiments [8]. This is an important validation exercise on real tokamak data for a code which is being used extensively to predict melt damage on the ITER divertor [1].

Simulations are performed first for L-mode plasma loads, without the complication of ELMs, and have been performed both for a reference, well aligned lamella and the misaligned element. Input heat loads are obtained from experimental data, notably high resolution infra-red (IR) thermography [9]. During ELMing H-mode, the calculated time dependent, 3D temperature distributions in the special lamella lead to extremely high temperature gradients at the leading edge (~10^6 K/m) and noticeable W evaporation. In fact, the simulations demonstrate that consistency with the measured IR temperatures is only possible if the impinging heat flux is factor g_s ~ 2-4 lower than expected from geometrical considerations (mitigation factor $f_s = 1/g_s$) [6,9]. Mitigation factor was discussed in detail in [6]. The code also indicates that that shielding by the evaporated tungsten prevents bulk melting between ELMs. Encouragingly, the simulations are also able to quantitatively reproduce the dimensions of the damaged area observed by high resolution photography after the first pulse in which melting was achieved. The principle mechanism responsible for the melting is identified as the jxB force due to the thermo-emission currents from the hot surface, which generate velocities up to 0.7 m/s in the direction observed experimentally. No melt splashing is expected on the basis of the MEMOS simulations of melt depth and melt velocity and none is found experimentally.

Analysis of importance of the **JxB** force generated by the thermo-emission current on melt layer damage of W monoblocks in the full-W divertor under ELM-like heat loads expected in ITER were performed using the code 3D MEMOS validated against JET-ILW experiments. Numerical simulations demonstrated that the **JxB** force produces negligible melt layer displacement in comparison with the melt layer damaged produced by the tangential friction force of the impacting plasma.

2. MEMOS CODE VALIDATION ON JET TRANSIENT EXPERIMENTS

2.1 HEAT LOAD SPECIFICATIONS IN THE JET-ILW EXPERIMENTS AND THE MEMOS MODELLING

The scheme of the experiments in JET-ILW is well described the ref. [4-6]: The outer JET divertor is split up in four so-called Stacks (A,B,C,D). In the stack A the special lamella was installed to allow significant preheating due to the front surface being exposed to the parallel heat flux Q_s in addition to the heat flux Q_n impacting to the top surface of the special lamella (Fig.1). The Q_s and Q_n are connected via geometric factor η which should be between 25 and 35 [4,6] ($Q_s = \eta Q_n$). The exposure to the parallel heat flux is achieved by producing a chamfered leading edge of 0.25-2.5mm and also lowering of the 8 lamellas in front of the exposed. The lamella has a poloidal extent of 5.9cm and is 5.5 mm wide toroidally. The adequate 3D geometry of the special lamella exposure installed into the code 3D MEMOS is demonstrated on the Fig.1. All sizes of experimental conditions are fully reproduced in the 3D MEMOS target geometry. As it was in the JET-ILW experiment: angle between B and surface has to be ~2.5^o, B = 2.87T, pressure of impacting plasma at the leading edge surface estimated from the pedestal data: ~ 6kPa in maximum of ELM and 0.01kPa in between ELMs with pressure shape corresponding to ELM shape, temperature of impacting plasma is taken about 400eV for ELMs. Due to rather high tungsten temperature achieved at the leading edge thermo-emission

current **J** (Richardson law) from the special lamella can appear during the ELMs that lead to action of the **JxB** force inside the melted tungsten. As it was observed in the TEXTOR experiments [2] in which it was found that the melt motion is generated dominantly by the thermo-emission current. This force is directed along the leading edge in poloidal direction. Simulations are performed for the JET-ILW H-mode JET Pulse No: 84779 with 51 ELMs during the special lamella exposure. Input heat loads for the 3D MEMOS simulations are obtained from experimental data, notably high resolution infrared (IR) thermography [9]. The time dependence of Q_s along the poloidal coordinate of the special lamella is demonstrated on Fig.2.

2.2 NUMERICAL MODEL OF THE CODE 3D MEMOS

The melt layer redistribution after multiple ELMs is simulated applying the fluid dynamics code 3D MEMOS [7,8] based on the measured heat flux data. The motion of melted material along the surface is described in the 'shallow water' approximation of the Navier-Stokes equations, with the surface tension, viscosity of molten metal, and the radiative losses from the hot surface taken into account. The plasma pressure gradients along the divertor plate, as well as the gradient of surface tension and the **JxB** force of the currents (external and thermo-emission) crossing the melt layer immersed in a strong magnetic field, produce the melt acceleration. To estimate thermo-emission current two approaches are implemented into the model and the code a) simple Richardson law b) model, in which space charge above the surface decreasing thermo-emission is accounted for in accordance with model developed in ref. [10].

The "shallow water" approximation is applied to the Navier-Stokes equations because the thickness of the melt layer is much smaller than the sizes of the molten layer and pressure gradients across the melt layer are absent. In this assumption a velocity components parallel to the surface exists only and a melt velocity averaged over the molten layer can be used for description of the melt motion. Fluid is assumed to be incompressible. Temperature dependent thermo-physical data are used.

To calculate the temperature field inside the target the 3D Stefan problem with moving boundaries attached to re-solidification, melting and vaporization fronts is solved using the splitting method. Temperature dependent thermo-physical data are used [11]. A model for plasma shielding well develop and, validated against experiments at plasma gun facilities QSPA-T and MK200UG, and described in details in [12], has been implemented into the code 3D MEMOS to take into account the influence of the evaporated material on the surface heat loads. For 3D simulations the following simplifications were assumed: self-similar solution is used for estimation of vapour expansion [13], mean charge model (by D. Post in coronal limit) is used for the plasma ionization estimation, impacting ions stopping inside the expanding vapour is accounting for only, heat conductivity and radiation from the plasma shielding to the wall are not accounting for.

2.3 RESULTS OF SIMULATIONS

Numerical simulations are carried out for the H-Mode JET-ILW JET shot Pulse No: 84779 with impact parameters described above for several mitigation factors $f_s = 0.2$, 0.3, 0.4, 0.5, and 1.0 with

and without plasma shielding accounting for. The mitigation factor f_s decreases Q_s calculated via geometric factor η to fit calculated temperature to the measured one [6].

Simulation with f_s= 1.0 demonstrate unrealistic maximum temperatures for individual ELMs exceeding 6000K and bulk melting of the special lamella during the pulse which was not observed in the experiments [4-6]. The best fitting of the experimental data (time dependences of the surface temperature, and measured vaporized tungsten) was obtained with a mitigation factor f_s = 0.4 and accounting for the plasma shielding [4-6]. Numerical simulations demonstrated that the surface temperature of the leading edge is below the melting point during the inter-ELM time intervals (Fig.3) and essentially exceeds melting point during each individual ELM while dropping within about several milliseconds after the ELM maximum. Moreover, the overheated region with extremely high temperature gradients at the leading edge (~10^6 K/m) and noticeable W evaporation is very narrow with typical scale of several hundred microns (Fig.4(a) and Fig.4(b)). At the inter-ELM time interval the temperature field of the top surface of special lamella is rather smooth (Fig.4(a)).

Noticeable W evaporation during ELMs leads to formation of plasma shielding in the front of the leading edge essential screening the impacting plasma leading to decreasing the surface temperature during the ELMs and preventing bulk melting at the later time moments (Fig.3). Bulk melting was not observed at any time in the experiments [4–6]. Typical melt layer thicknesses corresponding to the ELM maximum were about few hundred microns and final evaporation depth does not exceed 0.3 microns after 51 ELMs of JET Pulse No: 84779.

To determine the main driving force responsible for the melt layer redistribution on the special lamella as observed in the JET-ILW experiments two scenarios were simulated for a mitigation factor f_s= 0.4 scenario with plasma shielding:

a) all driving forces described above including **JxB** force are accounting for
b) **JxB** force is excluded.

The simulations demonstrate that the gradient of the plasma pressure due to the impacting plasma and the gradient of the surface tension generate a melt motion with a melt layer velocity of about 0.006m/s. This produces a final surface damage after one pulse with amagnitude of about 20 microns. During the ELMs the **JxB** force from the thermo-emission current is calculated in accordance with the Richardson law (Fig.5) and generates melt motion along leading edge in High-Field-Side direction with velocities of up to 1.5 m/s in the central molten region and up to 0.5m/s at the periphery in the direction observed experimentally (Fig.6). Such intense melt motion leads to redistribution of the molten material and producing the jet-like mountain and pattern of about 200 microns which well correlates with the one observed in JET-ILW experiment ones after single pulse (Fig.7).

3. INFLUENCE OF THERMO-EMISSION CURRENT ON MELT MOTION IN JET-ILW EXPERIMENTS AND ITER TRANSIENT LOADS

In the TEXTOR experiments studying melt damage on tungsten limiter structures implemented into close to the last closed flux surface [2] it was observed that the thermo-emission current causing the melt motion was significantly less than it follows from the Richardson law. Here the following

mechanisms can lead to a decrease in the thermo-emission current from the surface heated by the plasma in strong magnetic field being parallel to the surface: Impacting plasma covers the heated surface and the thermo-emission electrons escaped from the surface thus producing a space charge above the surface. The space charge produces a negative potential, which decrease the thermo-emission current [10].

In case of strong magnetic field being parallel to the surface, thermo-emission electrons escaping from the surface can partly return back to the surface due to the gyro rotation around the magnetic field lines. That leads to additional decreasing the total thermo-emission current.

Both mechanisms described above are important for ITER transient loads, in which impacting plasma heat loads impact rather large scale surfaces with relatively uniformly. Formation of such a space charge and gyro rotation of thermo-emission electrons leads to rather low total thermo-emission current (TEXTOR experiments [2]).

To demonstrate the suppression of melt motion caused by the **JxB** force numerical simulations of ITER W monoblock damage under multiple ITER ELM-like heat loads are performed by the 3D MEMOS code. Absorbed energy density of ELMs at the monoblock surface was taken about 1.1MJ/m^2 with uniform energy distribution along the heated area. Simulations are carried out for the wide region of plasma pressures expected in ITER ELMs P = 0.02, 0.5 and 0.8 bars. Triangle pulse shape of ELM is assumed with duration about 0.7ms and 0.35 rise time. Overall impact angle of magnetic field lines at the top monoblock surface is about 4.5 degree. Depth of tungsten armour is taken about 2mm with water cooling of W monoblocks from the back side. ELM frequency – 5Hz, B = 2.65T. Due to negligible evaporation (about 0.00067 microns per each ELM) vapour shielding above the monoblock surface is not formed and tangential friction force of impacting plasma causes the melt motion. Thermo-emission current is calculated in accordance with model [10]. The simulations are performed for the target consisting of 4x4 monoblocks (each monoblock has 28mm in toroidal direction and 12mm in poloidal, gap width – 0.05mm, each monoblock has toroidal chamfer with chamfer height 0.5mm) geometry demonstrated on Fig.8. Leading edges of monoblocks are shadowed.

Final erosion profiles of single monoblocks after 100 ELMs are demonstrated on Fig.9 for the scenario P = 0.02 bars, on Fig.10 for the scenario P=0.5 bars, and on Fig.11 for the scenario P = 0.8 bars. For the calculated scenarios the melt layer thickness does not exceed 15 microns for each ELMs, the velocities of melt motion are below the critical velocities for droplet splashing and gap bridging. It is clearly seen that amplitude of surface damage in toroidal direction linearly depends on the pressure of impacting plasma respectively 10, 95 and 142 microns after 100 ELMs (0.1, 0.95 and 1.42 microns per single ELM). Erosion in the toroidal direction dominates and it is produced by the tangential friction force of the impacting plasma. Numerical simulations demonstrated that in the poloidal direction melt motion damage caused by the **JxB** force with Richardson thermo-emission current limited by the space charge is small (see Fig.9). After 100 ELMs erosion is about 1.3 microns (0.013 microns per ELM). It should be pointed out that the **JxB** force generated by thermo-emission current can leads to the noticeable melt motion damage of ITER tungsten armour

in the regions with sharp temperature gradients (sharp heat load gradients). Influence of the **JxB** force on W armour erosion of ITER armour under transients with sharp heat load gradients has to be further numerically investigated.

For the JET-ILW experiments both mechanisms of the thermo-emission current limitation do not work. Impacting plasma interact with the very small target region and melted thickness in direction across the lamella is about 200–300 microns (see Fig.4b). Thermo-emission current, which can produce melt motion, is produced by the electrons escaping from the top surface of the special lamella in perpendicular direction to it. Due to small sizes of melted layer along the magnetic field lines space charge formed above the top lamella surface is shifted by the plasma stream along the top surface to the region with the low temperature. Thus space charge cannot prevent emission of thermo-electrons from the melted layer.

The second mechanism is not work also. The electrons leaving and rotated around the magnetic field line impact at the surface mostly far away from the melted layer due to microns sizes of the melted layer in the direction of the magnetic field line. Thus in JET-ILW experiments thermo-emission current causing melt motion along the special lamella is determined by the Richardson law.

CONCLUSIONS.

3D Model for multi-ELM JET-ILW experiments is implemented into MEMOS and applied for modelling shots JET Pulse No: 4514 (L-mode) and JET Pulse No: 84779 (H-mode) and verified against experimental data.

MEMOS simulations for the special lamella damage are performed using different mitigatio factors f_s to thermal loads Qs.

The simulations for shot the JET Pulse No: 84779 with mitigation factor $f_s = 0.4$ and accounting for the plasma shielding appropriately fit the experimental data: time dependences of the surface temperature, and measured vaporized tungsten.

It was demonstrated that the plasma shielding play substantial role in decreasing heat loads during the ELMs. The shielding prevents bulk melting.

The **JxB** force with the thermo-emission current **J** is the main driving force of the melt motion damage in the JET-ILW experiments.

It was demonstrated negligible melt motion damage in poloidal direction caused by the **JxB** force with with Richardson thermo-emission current limited by the space charge for ITER scenarios of multiple ELM loads on monoblocks in the full-W divertor. Tangential friction force of the impacting plasma dominates in total erosion and erosion depends linearly on plasma pressure.

It should be pointed out that the **JxB** force generated by thermo-emission current can become noticeable in the regions with sharp heat load gradients. Influence of the **JxB** force on W armour erosion of ITER armour under transients with sharp heat load gradients has to be further numerically investigated

ACKNOWLEDGEMENTS

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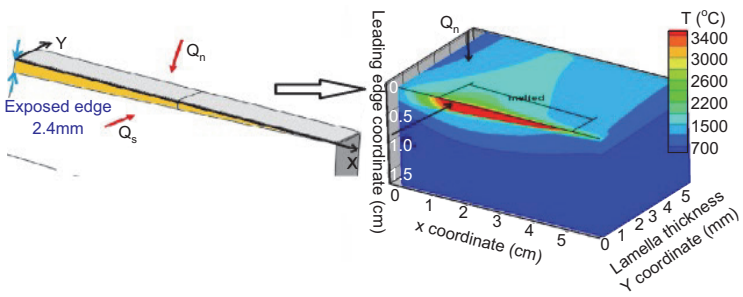

Figure 1: Sketch of Special Lamella installed in JET-ILW and sketch of the tungsten target used in simulations.

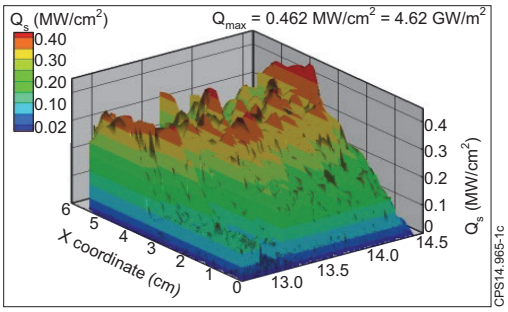

Figure 2: Time dependence of input flux Q_s along the poloidal direction (X) for the shot JET Pulse No: 84779 used in simulations.

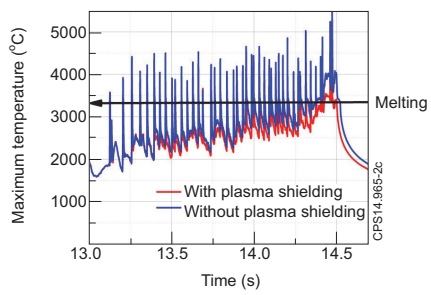

Figure 3: Time dependence of maximum of surface temperature along leading edge of special lamella.

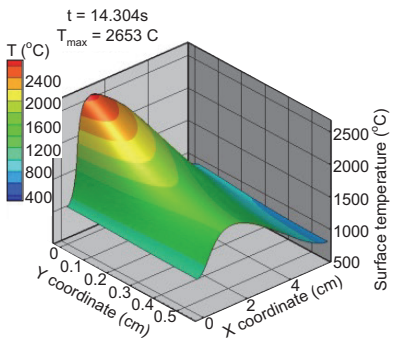

Figure 4: (a) Contour plots of the surface temperature at the top surface of special lamella at inter ELMs time t = 14.304s.

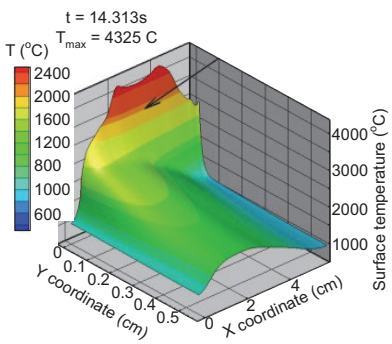

Figure 4: (b) Contour plots of the surface temperature at the top surface of special lamella at time corresponding to ELM maximum t = 14.313s.

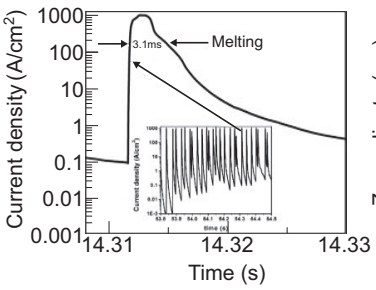

Figure 5: Time dependence of calculated mean thermo-emission current at the leading edge during a typical ELM. Figure inside demonstrates time dependence of the current for time interval including several tens ELMs.

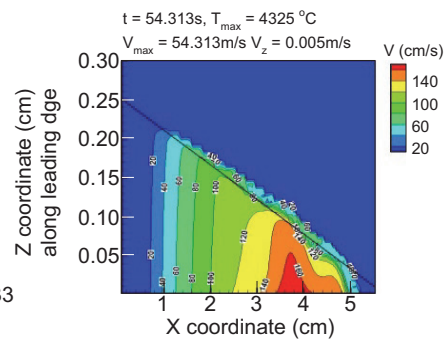

Figure 6: Contour plots of the melt layer velocity at the leading edge surface of special lamella at the time corresponding to the ELM maximum t = 14.313s.

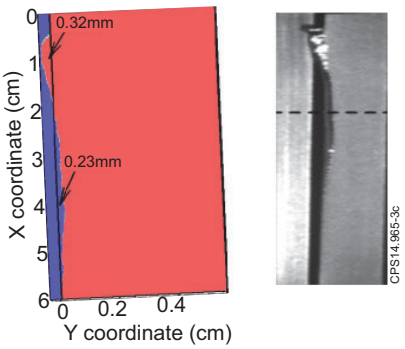

Figure 7: Final calculated surface profile view from the top surface (Left) and view of Specuial Lamella damage (right).

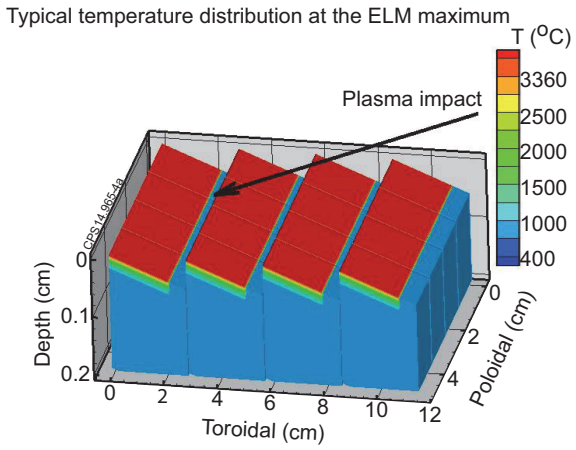

Figure 8: Sketch of the tungsten target used in simulations of ITER multi ELMs impact scenario.

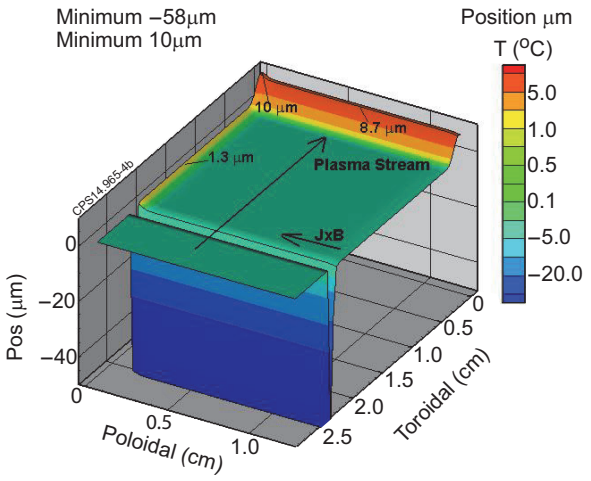

Figure 9: Final erosion profile of single monoblock after 100 ELMs.P=0.02 bars.

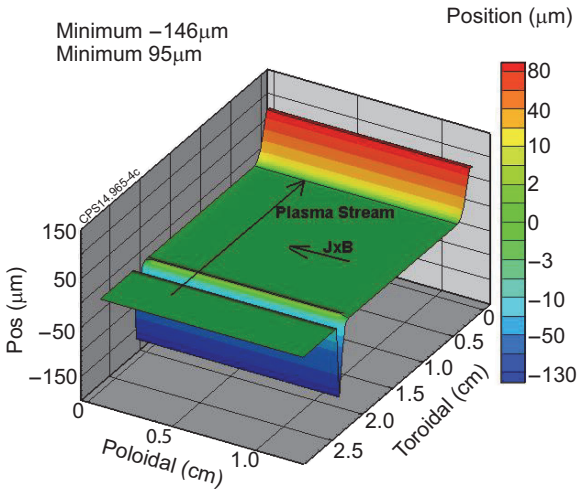

Figure 10: Final erosion profile of single monoblock after 100 ELMs.P = 0.5 bars.

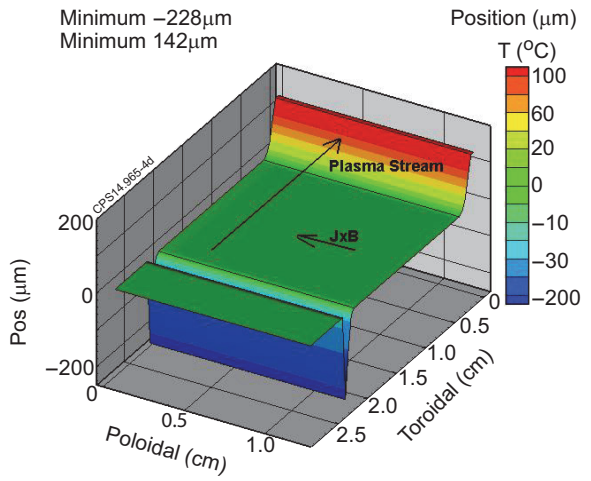

Figure 11: Final erosion profile of single monoblock after 100 ELMs.P = 0.8 bars