Conceptual design of a pre-loaded liquid lithium divertor target for NSTX-U

Citation for published version (APA):

Document license:
CC BY

DOI:
10.1016/j.fusengdes.2016.08.020

Document status and date:
Published: 15/11/2016

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain.
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 01. Nov. 2020
Conceptual design of a pre-loaded liquid lithium divertor target for NSTX-U

P. Rindt, N.J. Lopes Cardozo, J.A.W. van Dommelen, R. Kaita, M.A. Jaworski

Eindhoven University of Technology, Science and Technology of Nuclear Fusion Group, Eindhoven, The Netherlands
Princeton Plasma Physics Laboratory, Princeton, NJ, USA

HIGHLIGHTS

- Novel pre-filled divertor target design.
- Novel wicking model for prediction of capillary flow.
- Novel use of liquid metal as an interlayer to reduce thermal stresses.

ABSTRACT

In this work, a conceptual design for a pre-filled liquid lithium divertor target for the National Spherical Torus Experiment Upgrade (NSTX-U) is presented. The design is aimed at facilitating experiments with high lithium flux from the plasma facing components (PFCs) in NSTX-U and investigating the potential of capillary based liquid lithium components. In the design, lithium is supplied from a reservoir in the PFC to the plasma facing surface via capillary action in a wicking structure. This working principle is also demonstrated experimentally. Next, a titanium zirconium molybdenum (TZM) prototype design is presented, required to withstand a steady state heat flux peaking at 10 MW m⁻² for 5 s and edge localized modes depositing (130 kW) in 2 ms at 10 Hz. The main challenge is to sufficiently reduce the thermal stresses. This is achieved by dividing the surface into brushes and filling the slots in between with liquid lithium. The principle of using this liquid “interlayer” allows for thermal expansion and simultaneously heat conduction, and could be used to significantly reduce the demands to solids in future PFCs. Lithium flow to the surface is analyzed using a novel analytical model, ideally suited for design purposes. Thermal stresses in the PFC are analyzed using the finite element method. The requirements are met, and thus a prototype will be manufactured for physical testing.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

In the process towards a commercially viable fusion reactor, one of the major challenges lies in the integrity and lifetime of materials. Tokamaks currently suffer from excessive wall damage in the plasma exhaust region [also called divertor], partly due to the high particle and power load. Even tungsten, the plasma facing material considered for ITER, erodes too quickly for a commercial reactor [1]. One of the dominant damage mechanisms being erosion.

As an alternative to solid materials, the use of liquid metals is proposed. A liquid is not vulnerable to erosion, because when material is removed it can easily be replenished. Another advantage is that any particles from the plasma retained in the liquid can be filtered out when the liquid is circulated, which can reduce the tritium inventory for example. Currently one of the most researched candidates is liquid lithium (LL). Using LL has the additional benefit that a vapor cloud in front of the plasma facing component (PFC) is formed, which acts like a shield and thus reduces the power to the PFC [2,3]. A similar mechanism exists for tin [4]. Also, LL allows for a low recycling operating regime, due to its great affinity with hydrogen species. This can ultimately lead to enhanced plasma performance [5,6].

Two important open questions in the design of LL PFCs are (1) how does lithium interact with the plasma, and (2) how can the plasma facing surface (PFS) effectively be supplied? Elaborate limiter studies with LL have been done on T11-M and the Frascati Tokamak [2,7]. LL divertor experiments have only been done on NSTX [8]. These studies have never operated lithium components at...
high temperatures, i.e. a maximum of 600 °C for the limiters on the T11-M and Frascati reactors and 300–400 °C for the NSTX divertor. As for the LL supply, a full cycle in which LL is filtered and recirculated has not been attempted yet. Most limiter designs involve the use of a so called capillary porous system (CPS), introduced in [8,10]. A CPS is some type of capillary medium (e.g. a fine mesh) in which the liquid is confined by capillary forces. When there is a local shortage of liquid, these same forces automatically supply new liquid. In some cases, LL is supplied to the CPS from a reservoir, driven by either capillary forces or external pressure (as in the CDX-U tokamak rail limiter [6]). Also more advanced flowing limiter schemes have already been tested [11]. In the case of the NSTX divertor, however, the only technique used so far has been to evaporate lithium onto the PFCs, depositing µm thick coatings [8], which is repeated as soon as the lithium is depleted.

In this work, a conceptual design for a pre-filled LL divertor target for NSTX-U is presented (Fig. 3), along with a prototype design (Fig. 6). The target PFS will be supplied with lithium from an internal reservoir. LL transport will be facilitated by capillary forces acting in a wicking structure, which will provide a much larger availability of LL at the surface compared to the evaporative scheme used before. This can be exploited to research the performance of LL PFCs operating at temperatures up to >1000 K and corresponding high lithium flux, while avoiding drying of the surface. The largest challenge in the design will be to keep thermal stresses within acceptable range.

To get to the design, a set of requirements is first derived. Then a concept design is formulated, based upon the principles of passively supplying LL to the surface using capillary forces. This principle is also demonstrated in a simple test setup using isopropanol instead of lithium. A detailed prototype design is then made, the critical dimensions of which have been tuned using a finite element model (minimizing thermal stresses) and an analytical flow model (maximizing LL flow to the surface). The performance of the prototype has been assessed through the same models, indicating that it meets the requirements.

2. Design requirements

The liquid lithium divertor target (LLDT) should meet the following requirements, which have been formulated based on discussion with the NSTX-U team, literature and basic calculations.

- The substrate must be a fusion relevant high Z material.
- PFC must survive surface temperatures up to 1000 K.
- PFC must survive peak heat steady state heat-flux of 10 MW m⁻² when there is combined with edge localized modes (ELMs) of 130 kJ in 2 ms at a frequency of 10 Hz, for maximum 5 s.
- LL on the surface must be stable to droplet ejection.
- PFC must be pre-loaded with LL before installation in NSTX-U.
- LL must be liquefied in the time available between shots (20 min).
- It must be possible to clean the LL on the surface so that it is optically clean (reflective).
- PFC must directly replace the original high Z components as installed in row 3 (Fig. 1) of the outboard divertor, without the need for additional modifications to the divertor.
- PFC must inertially cool to 460 K within 20 min.

As calculated by Abrams [12], when considering only pure evaporation, this leads to an evaporation rate of around one order of magnitude higher. Though this may raise concerns, no experimental data exists for the behavior of tokamak plasmas exposed to lithium at this high temperature. Gathering this data is exactly what this component must facilitate.

The component can be heated to this temperature by the plasma heat flux, which peaks at the specified 10 MW m⁻² when the strike point is placed on the LLDT. Surviving this heat flux and temperature is defined as: no plastic deformations or recrystallization in the component, and no dry spots on the surface in order to avoid erosion of the high Z material. Given the short duration of the heat load on the component, the yield strength is chosen as the limit beyond which plastic deformation occurs. Creep effects are considered negligible on this timescale.

The heat flux profile is derived in several steps. A free-boundary equilibrium solver was used to determine a plasma discharge shape resulting in a strike-point at the candidate position and consistent with NSTX-U coil limitations. The maximum heating power to this plasma for a given βₚ is then derived using the ITER ELMy H-mode confinement scaling. These previous steps follow the same procedure as utilized for the NSTX-U design study in [13]. The heat flux is predicted from the magnetic flux expansion for the derived equilibrium and the expected scrape-off layer heat flux profile measured in NSTX previously [14]. Based on the heat-flux scaling width and the equilibrium plasma shaping, an assumption that 100% of the power exhausts to the outboard divertor results in a value far in excess of present material limitations, but is simultaneously unrealistic due to power splitting between divertor legs and radiative processes in the plasma. To provide a reasonable design target, the heat-flux profile is scaled to yield a maximum value of 10 MW m⁻², shown in Fig. 2, which is considered a reasonable and significant value similar to previous measurements in the NSTX [14].

2.1. Minimum required capillary flow

To avoid dry spots on the surface, the LL supply must always be able to match the net loss rate from the surface. Measured erosion yields [12] are not used, since they are dependent on temperature and thus the thermal response of the design, which is not yet known. Also, these yields have not yet been validated on tokamaks. Instead, an estimate of the net loss rate is made by assuming that all incoming power from the plasma goes into gross erosion.
of the lithium through evaporation. Power dissipation by heating of the divertor and possibly vapor shielding are neglected. This estimate thus represents a conservative approach by potentially over-estimating both the lithium erosion yield and the absorbed energy.

To then calculate the net erosion, a redeposition factor, $R$ must be taken into account. This factor was measured by Abrams [15] and may be very high, $>99.5\%$. In this work a more pessimistic estimate of $R=0.95$ is made. Eq. (1) describes the volumetric loss rate $Q_{\text{loss}}$ for this case.

$$Q_{\text{loss}} = \frac{P_{\text{incoming}}}{E_{\text{vap}}} \cdot (1 - R) = \frac{P_{\text{ss}} + P_{\text{ELM}}}{E_{\text{vap}}} \cdot (1 - R)$$

(1)

Here $E_{\text{vap}}$ is the heat of vaporization per volume, $P_{\text{incoming}}$ is the total power deposited onto the divertor, i.e. onto all divertor components in row 3, which consists of 96 tiles. The load is assumed to be spread equally across all tiles. $P_{\text{incoming}}$ consists of the steady state power $P_{\text{ss}}$, and the additional power from ELMs $P_{\text{ELM}}$. $P_{\text{ss}}$ is obtained by multiplying the average power density (not peak) with the total surface area of the strike zone, and equals 6 MW. The energy of the ELMs is translated into a steady state power by dividing by 0.1 s. The peak power during the 2 ms of the ELM itself is not considered, since the energy of the ELM will only evaporate a small fraction of the lithium on this surface. This can be recovered during the rest of the ELM period. This results in the minimum required flow rate for the entire divertor $Q_{\text{min}} = Q_{\text{loss}} = 4 \times 10^{-2}$ L/s.

3. Concept design

The concept design is shown in Fig. 3. There are two working principles. First, as explained, LL from an internal reservoir is provided to the surface via a capillary channel or wick. Lithium is distributed across the surface also by capillary forces, which arise due to a texturing applied on the surface. These capillary forces also serve to stabilize the liquid against droplet ejection.

Second, thermal stresses in the component are relieved by using a castellated bulk. This can be seen in the prototype, Fig. 6. Thermal stresses must be relieved because these can be extremely high due to the large tile size in NSTX-U. The slots in between the individual brushes allow for thermal expansion, thus relieving the stress. Note that these slots have a dual function. They also serve as capillary wicking channels. Thus they are filled with LL. This is important because the LL allows for heat conduction across the slots. This is required because the component is not actively cooled, and otherwise sharp temperature peaks would occur. The combined function of the slots allows for compactness and more simple manufacturing. Compactness and simplicity are especially important given the limited amount of design space.

The last important feature of the concept is that it will be pre-filled. This means the reservoirs will be filled before the component is installed in the reactor, and also that the wicks and plasma facing surface will be wetted. In practice this will entail filling the reservoirs with solid or liquid lithium in a controlled environment, such as a glovebox. Wetting in all areas should be achieved by subsequent heating and manual distribution of the lithium with thin tools if required. Of course, protective measures must be applied to prevent contamination of the lithium during installation.

3.1. Preliminary testing for proof of principle

A preliminary test has been done which has demonstrated that lithium can indeed be supplied to the surface using only capillary forces. A stainless steel test piece was used that has the key features of the concept: a wicking channel and a textured surface. A CAD drawing of this proto-prototype is shown in Fig. 4. The green face indicates a cross section, which shows the internal geometry. The reservoir is filled with isopropanol and the wicking front on the surface is observed with a camera from above.

Two snapshots of the results are shown in Fig. 5. On the top a flame sprayed plate has been used as a porous surface (similar to the original liquid lithium divertor plates in NSTX [8]). On the bottom the plate has been replaced with piece of KIMTECH Pure cleanroom wipe, which is essentially a tightly woven cloth. The wicking principle seems to work in both cases, because the isopropanol has clearly risen through the wick and wetted part of the surface around it. Though, it appears that the cleanroom wipe is much more effective. Almost the entire wipe is wetted, whereas the flame sprayed plate is only wetted up to a few mm from the wick. Given this observation, selecting a suitable surface for the
4. Prototype design

The prototype design is shown in Fig. 6, and has an outer geometry almost identical to the original NSTX-U divertor tiles. The only difference is that it is perfectly rectangular, rather than slightly trapezoidal, and it is 12.7 mm (0.5 in.) taller (in z-direction) to generate sufficient space for the internal geometry. The characteristic dimensions are derived from the analytical model and finite element (FE) model presented in Sections 4.3 and 4.1. The capillary channels that separate the brushes and reach into the tube shaped reservoirs must have a width of $2r_w = 300 \mu$m. The pores in the porous surface must have a radius of $r_p = 25 \mu$m. Fully dimensioned CAD drawings can be found in the 3TU data repository [16], along with Matlab files and COMSOL files for the analytical and FE model, respectively. The material data used is given in the appendix of this paper.

As mentioned in Section 3.1, selecting the type of surface is an open issue. Candidates are a laser textured surface (as tested by Lin et al. [17]), a plasma sprayed surface, and a wire mesh. The laser texturing could also be replicated using electrode discharge machining (EDM), although the characteristic dimension of the resulting texture will be a few times larger for EDM. Note that the model presented in Section 4.3 does make an assumption for the type of surface, which might not be the one ultimately used.

The prototype will be manufactured from titanium zirconium molybdenum (TZM). This alloy is preferred over tungsten, despite slightly worse mechanical and thermal properties, because it is easier to machine. The selected TZM grade is ASTM B686 363/364. This material grade is deformation strengthened to achieve a yield strength of at least 585 MPa for the bulk. All fine geometry will be created via EDM. Due to this manufacturing process the reservoirs will be open at both ends, so thin walls will be bolted to the sides to close off the reservoirs.

The existing interface to the reactor wall is the so called T-Bar, which must fit inside the T-shaped slot in the component. Direct contact between the slot and the T-bar will be prevented by either a ceramic coating or a washer. This ceramic layer will be tuned to minimize the heat loss to the reactor through conduction, while still allowing the component to cool sufficiently in between shots. The ceramic layer will also provide electrical insulation, which facilitates more effective glow discharge cleaning of the lithium surface.

4.1. Finite element model of thermal response

An FE model was made in COMSOL 4.4.0.248, to assess whether the achieved surface temperatures are in the desired range, and to make sure thermal stresses remain within the tolerable range. For the output, both temperature $T$ and thermal stresses (and components) are evaluated locally at any point in time. To evaluate the severity of the thermal stresses, a normalized stress is calculated locally, which is defined as the magnitude of the Von Mises stress over the yield stress, $\sigma' = \sigma_{\text{Mises}} / \sigma_{\text{yield}}(T)$.

A simplified geometry is used to minimize the required computational power, and is shown in Fig. 7. Boundary conditions are also indicated. Plasma discharges of different intensity are simulated by varying the plasma heat flux profile $Q_p$. Fig. 2 shows the heat flux profile scaled to the required 10 MW m$^{-2}$. In this case the initial temperature is set to 460 K. $Q_p$ is only used to analyze pre-heating of the component, and is in this case set to 200 W. Both heat loads are constant in time. Most notably in Fig. 7, only one brush is modeled. The surrounding material is identical to the rest of the prototype, except that it is modeled to have no stiffness. This way, the stress-relieving effect of the slots is mimicked, and heat transfer can still be analyzed. The design is modeled in both pure tungsten and the selected TZM grade.
Fig. 6. Detailed overview of the prototype design. Outer dimensions correspond to original row 3 tiles. Only height has been increased by 12.7 mm (0.5 in.) to accommodate the internal features of the design. The wicking channels are 300 μm wide. A thin wall is bolted to each side of the component to keep lithium from leaking out of reservoir and wick ends.

The width, length and depth of the brushes influence the thermal stresses in both the brushes themselves and the material below them. These parameters are tuned so that, for the heat flux at which the surface temperature reaches the recrystallization temperature, the stresses remain just below the yield stress. Of course, the width and length of the brushes are chosen so that there is a whole number of brushes in all directions.

4.2. Prototype thermal response

In the analysis, two different materials are considered, pure tungsten and TZM. Also two different designs are considered. The first is the prototype design presented here. The second is an almost identical design, that features lamellae, oriented in the r direction, instead of brushes. Results for the latter are only included to illustrate the effectiveness of the brushes.

Fig. 7. Simplified geometry used in the FE model. The nodes in red are fixed in the indicated directions. The plane in which these nodes lie is also a symmetry plane. The red line indicates the rough shape of the heat load profile Q_{maj}. Only one brush is modeled to further reduce computing time. The brush and the material below are modeled as TZM. The material surrounding the brush is also TZM, but has no stiffness (purple). This way the stress relieving effect is mimicked, while the load transfer is still modeled. The steel bar (purple) also has no stiffness, and has a bottom surface temperature fixed at 300 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Output of the FEM model for a plasma heat load of maximum 10 MW m^{-2} on a TZM target at \( t = 4.83 \) s into the discharge. The upper plot shows the normalized stress. The lower plot shows the temperature in Kelvin. The largest stresses occur in the side face, which is not where the peak temperature occurs. Low stresses occur in the brush. The stress concentration at the base of the brush is qualitatively correct, but the quantitative results are not considered reliable due to insufficient mesh refinement and unrealistically sharp corner geometry.

Figs. 9 and 10 show the peak temperature and maximum normalized stress in the prototypes according to the FE simulations as a function of the steady state heat load. Where these maxima occur can be seen in Fig. 8. Peak stresses at the base of the brush
are not considered physical, since these are due to unrealistically sharp corners, and insufficiently mesh refinement. The recrystallization temperature is also indicated for both tungsten and TZM, obtained from [18,19], respectively.

Clearly, the brush design performs adequately for both materials, at the required steady state heat load of $10 \text{ MWm}^{-2}$. The normalized stress does not exceed 0.7 and the temperature remains below the recrystallization temperature, yet does reach the required 1000 K. As expected, though, the peak temperatures and thermal stresses are lowest in tungsten. The reason is that tungsten has a better thermal conductivity. This allows for lower surface temperatures, due to a decreased temperature gradient. The latter leads to lower thermal stresses. Of course, tungsten also has a higher yield strength.

The pre-heating and cooling times are also assessed using the FE model. Fig. 11 shows the temperature response of the point on the surface which lies directly beneath the peak of the heat load. Radiation to the environment was found to be insignificant due to the low emissivity of liquid lithium and is not taken into account. Pre-heating and cooling are achieved in ~600 and ~325 s, respectively. Note that in this analysis the pre-heating is assumed to start from room temperature, which in reality only occurs for the first shot.

4.3. Analytical model of capillary flow

To evaluate the lithium flux to the surface, a model is made using the Darcy equation, in which the trajectory is composed of $n$ sections positioned in series. The flow through the complete trajectory (the wick and the surface) is calculated, assuming a summation of flow resistances. In reality, there are of course also parallel sections. E.g. the two wicks from the reservoir represent two parallel sections. However, when parallel sections are identical, they can be represented by a single flow resistance with a surface area of the parallel sections combined, which is the case here.

$$Q \cdot R_{\text{tot}} = \Delta P$$

$$R_{\text{tot}} = \sum_{i=1}^{n} R_i; \quad R_i = \frac{\mu L_i}{k A_i}$$

Here $Q$ is the volume flux, $k$ is the permeability of the medium, $A$ is the cross section, $\mu$ is the viscosity, $L$ is the length of the section. $k$ is approximated for the porous surface, as a function of the pore radius $r_p$ and void fraction [20]. For the wick, the permeability $k$ is derived from the Poiseuille flow for parallel plates, so $k = r_p^3/3$. The net driving pressure, $\Delta P$, is made up of the forward capillary pressure minus the backward capillary pressure and the magnetic drag in each section.

$$\Delta P = \frac{2 \gamma \cos \alpha}{r_p} - \frac{2 \gamma \cos \alpha}{r_w} - \sum_{i=1}^{n} \frac{\sigma B^2 dL_i}{dt}$$

(4)

Here $\gamma$ is the surface tension, $\alpha$ is the contact angle, $\sigma$ is the electrical conductivity, $B$ is the magnetic field strength, and $dL_i/dt$ is the speed in a specific section. All flow is assumed to be purely perpendicular to the magnetic field. There are two terms for the capillary pressure. The first drives the liquid towards across the porous surface. The second is for the worst case scenario when the reservoirs are empty, and the reverse capillary front sits in the wick and drives the flow back into the reservoir. Gravity is negligible because of the low height of the trajectory. The properties of the lithium are evaluated at 600 K. Inserting Eq. (4) into (2) provides us with an expression for the volume flux.

$$Q = \frac{2 \gamma \cos \alpha / r_p - 2 \gamma \cos \alpha / r_w}{R_{\text{tot}} + \sigma B^2 \sum_{i=1}^{n} L_i / A_i}$$

(5)

Finally, the model has also been verified against the prototype tests where the KIMTECH wipe was used. The speed of the wicking front has been determined for multiple experiments, in both the upward and downward direction indicated in Fig. 5, and is shown in Fig. 12. Since the actual “pore radius” of the wipe is not known, both a minimum and maximum estimate of the radius were used to predict the wicking speed. Both these predictions seem to roughly match the measurements, despite using the model from [20] to calculate permeability for open foams. The large variation
in the measurements is attributed to the optical method for finding the position of the wicking front (which is hard to distinguish), and inhomogeneities and impurities in the wipe. The latter must also be the cause of the non-uniform wicking front. The measurements beyond 12 mm and with negative flow speeds are considered outliers. The latter are presumably caused by accidental shifting and wrinkling of the wipe.

4.4. Prototype capillary flow

Fig. 13 shows the lithium volume flux to the PFS as a function of \( r_w \) and \( r_p \). Note that all values on the surface represent the maximum achievable volume flux. In other words, the lithium flux will be able to match the loss flux from the surface up to this rate, but if there is no need for replenishment it is not high. Also, the volume flux for the design values of \( r_w \) and \( r_p \) is indicated. The design values have been chosen as close as possible to the optimum for \( Q \), but they are restricted by manufacturing processes.

Based on the model, the achievable volume flux is almost 10 times higher than the requirement. Although experimental validation is limited, the behavior of the model seems logical. The flow to the surface peaks when \( r_p \) is lower than \( r_w \), and thus there is a net capillary pressure which drives the LL to the surface. When \( r_w \) is smaller than \( r_p \), LL is driven back into the reservoir. When both parameters are too low or too high, the net flow is very low, due to lack of permeability or capillary pressure, respectively. This increases the confidence in the model, despite the limited experimental validation.

The thermal expansion of the wicks is taken into account. The width of the wicks decreases during the plasma exposure, because the tops of the brushes are heated and expand, while the bottom stays cool. The FE simulation indicates the width of the channel could decrease up to 60 \( \mu m \) at the top. This decrease is accounted for in the flow model by decreasing the width of the entire wick. The result is a decrease in lithium flux of only 5%.

Finally, remember that the surface texturing also serves to stabilize the liquid against droplet ejection. The design value for \( r_p \) is compared against stability criterion derived by Jaworski [8], and is found to be well within the stable region.

5. Discussion

As shown, thermal stresses are dissipated very effectively by the castellated surface. After closer study of the simulation results, Fig. 8, it appears that the peak stresses do not occur on the top surface of the brushes, but below them, where the temperature is much lower. This is advantageous, since the yield strength strongly decreases with temperature.

The surface temperature is more critical, especially for TZM. However, it must be noted that the recrystallization temperature for TZM taken from [19] is measured for a grade with a yield strength of \( \sim 900 \) MPa. The cold or hot work, needed to achieve this strength, generally lowers the recrystallization temperature. This is due to the increase of internally stored energy in the metal, which is a driving force for the recrystallization process. Hence, the recrystallization temperature for the grade used, is estimated too low here.

Additionally, the predicted surface temperature is likely too high. In reality, the lithium on the surface will limit the surface temperature when the vapor pressure reaches an equilibrium with the plasma pressure. This is reported for tin by Van Eden et al. [4]. Although no literature exists yet which allows for reliable and accurate prediction of the exact temperature of the lithium, it is expected the equilibrium temperature is lower than the surface temperature predicted here.

The predicted flow also seems promising, even when taking into account the decrease in width of the wicking channels due to thermal expansion. The estimated flow, however, is only a lower bound, since the model assumes an empty reservoir and thus a strong capillary force in the wick, driving the LL back into the reservoir. The model (reservoir assumed full) has been validated against
the proto-prototype experiment, and shows agreement. The most important outcome of these experiments, though, is the importance of using the right wicking medium on the surface.

The flow requirement, \( 4 \times 10^{-2} \) L/s, was originally estimated by assuming that all incoming power was spent on evaporation of the lithium. A better estimate can be made, now that the surface temperature is available. The atomic yield of lithium was fitted as a function of temperature from the data obtained by Abrams et al., shown in Fig. 4 of [22]. The loss rate was obtained by combining the latter with the surface temperature from COM-SOL, an assumed homogeneous particle flux of \( 2 \times 10^{24} \) m\(^{-2} \) s\(^{-1} \), and a recycling coefficient of 0.95. The maximum loss rate, which occurs when the surface is hottest, was found to be \( 1.5 \times 10^{-4} \) L/s. This corresponds to a decrease of thickness of the lithium layer of \( \sim 2 \times 10^{-7} \) m/s. To put this number into perspective, the predicted erosion of W in the ITER divertor is on the order of nanometers per second [1].

5.1. Outlook

In the trajectory toward implementation of the LLDT in NSTX-U, first prototype tests are required to check whether the performance of the design is sufficient and matches the predictions. Practical issues must also be investigated, e.g. possible clogging of the wicking channels by impurities, or leaking of lithium from the reservoirs. These experiments are planned on the linear plasma device Magnum-PSI [23] for the fall of 2016. Although, as mentioned in Section 3.1, before a prototype can be manufactured, a suitable CPS type has to be selected for the surface. Based on the prototype tests, the LLDT design can then be finalized before the end of 2016, and potentially be implemented on NSTX-U for the FY2018 experimental campaign.

6. Conclusion

A new LLDT is required for NSTX-U, aimed at research into tokamak operation with high lithium flux from the PFCs, and investigating the potential of capillary based LL components. To this end, a set of requirements was formulated, a concept design was made, a detailed prototype design was made, and the performance was evaluated. Based on an analytical model for the lithium flow to the PFS and a finite element model for the thermal response, it is predicted that the performance of the design will be more than sufficient.

There are two important results from the design process that will impact further development of the LLDT for NSTX-U and possibly any future liquid lithium divertor design. Both are related to the main working principles of the concept design. First, the concept utilizes capillary forces in a wick and a surface texturing to transport LL to and across the plasma facing surface. A preliminary test, aimed at demonstrating this principle, has shown the importance of the surface texturing. A flame sprayed surface showed extremely poor performance compared to woven KIMTECH wipe. For the development of the NSTX-U LLDT, it is therefore essential to further investigate different surface types for the prototype and final design.

Second, the slots in between the brushes are filled with LL, to minimize thermal stresses while still allowing for thermal conduction across the slots. In general, a liquid metal interlayer will always allow for thermal expansion of its neighboring solids without any resistance, yet still conduct heat. The importance of this general principle is stressed, because it has the potential to reduce the demands on solid materials significantly in future PFCs.

### Appendix A. Material properties used

The material data used in this work are given in the tables below. Respective sources are also indicated.

<table>
<thead>
<tr>
<th>TZM properties</th>
<th>Temperature in Kelvin.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength ( \sigma_y ) (MPa), Fitted from data in [29].</td>
<td>2.5 \times 10^{-4}T^2 − 1.37 + 1.695 \times 10^{4}</td>
</tr>
<tr>
<td>Young’s Module ( E ) (Pa), Temperature in °C [29].</td>
<td>391.448 + 1,316.0 \times 10^{-7} − 1.4838 \times 10^{-5}T^2</td>
</tr>
<tr>
<td>Coefficient of thermal expansion CTE (1/K).</td>
<td>3.16 \times 10^{-11}T^2 + 2.88 \times 10^{-10}T</td>
</tr>
<tr>
<td>Fitted from data in [30].</td>
<td>+4.44 \times 10^{-10}</td>
</tr>
<tr>
<td>Thermal conductivity ( k ) (W/mK). Fitted from data in [31,32,30,26].</td>
<td>−1.19 \times 10^{-11}T^2 + 7.26 \times 10^{-5}T^2</td>
</tr>
<tr>
<td>Heat capacity ( C_p ) (J/kgK). From data in [33].</td>
<td>0.02327+126</td>
</tr>
<tr>
<td>Density ( \rho ) (kg/m(^3)). From [25].</td>
<td>19300</td>
</tr>
<tr>
<td>Poissons ratio ( \nu ). Temperature in °C [29].</td>
<td>0.279 + 1.0893 \times 10^{-5}T</td>
</tr>
<tr>
<td>Recrystallization temperature for 1h annealing ( T_{rc} ) (K). From [18].</td>
<td>1650</td>
</tr>
<tr>
<td>Ductile to brittle transition temperature DBTT (K). From [34].</td>
<td>As worked: 80–200</td>
</tr>
<tr>
<td>Recrystallized: 400</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lithium properties</th>
<th>Temperature from [35].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic viscosity ( \mu ) (Pa s).</td>
<td>−4.164 + 0.6374 \times \ln(T) + 292.1/T</td>
</tr>
<tr>
<td>Surface tension ( \gamma ) (N/m)</td>
<td>0.398 − 0.147 \times 10^{-9}</td>
</tr>
<tr>
<td>Contact angle ( \theta ) (°) on TZM. Estimated from [36].</td>
<td>65</td>
</tr>
<tr>
<td>Electrical resistivity ( \rho_e ) [ωm]</td>
<td>−64.9 + 1.064T − 1.035 \times 10^{-3}T^2 + 5.53 \times 10^{-7}T − 9.23 \times 10^{-12}T^4</td>
</tr>
<tr>
<td>Heat of vaporization ( E_{vap} ) [J/L]</td>
<td>1 \times 10^{7}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel properties</th>
<th>Young's Modulus ( E ) (Pa)</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of thermal expansion CTE (1/K)</td>
<td>12.3 \times 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity ( k ) (W/mK)</td>
<td>44.5</td>
<td></td>
</tr>
<tr>
<td>Heat capacity ( C_p ) (J/kgK)</td>
<td>475</td>
<td></td>
</tr>
<tr>
<td>Density ( \rho ) (kg/m(^3))</td>
<td>7850</td>
<td></td>
</tr>
<tr>
<td>Poissons ratio ( \nu )</td>
<td>0.28</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Al(_2)O(_3) properties</th>
<th>Young’s Modulus ( E ) (Pa)</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of thermal expansion CTE (1/K)</td>
<td>0.55 \times 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity ( k ) (W/mK)</td>
<td>18 \times 0.8</td>
<td></td>
</tr>
<tr>
<td>Heat capacity ( C_p ) (J/kgK)</td>
<td>880</td>
<td></td>
</tr>
<tr>
<td>Density ( \rho ) (kg/m(^3))</td>
<td>3600</td>
<td></td>
</tr>
<tr>
<td>Poissons ratio ( \nu )</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>