# THE SPALLATION TARGET FOR THE ULTRA COLD NEUTRON SOURCE UCN

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*A pulsed ultra cold neutron source UCN, based on the spallation process, is under construction at PSI. For the operation of UCN, it is foreseen to use a target which consists of an array of zircaloy tubes filled with lead and cooled by heavy water. The design of the target system will be presented, concentrating on the thermo-mechanical behavior of the zircaloy-clad Pb target and the beam window.*

## INTRODUCTION

A source of ultra cold neutrons, based on the spallation process is under construction at PSI. With the help of a fast kicker the whole ~1 MW proton beam (590 MeV, 2 mA) from the accelerator will be switched onto the UCN spallation target for approximately 8 seconds every 15 minutes. The spallation neutrons are thermalized in a large heavy-water moderator at room temperature and further cooled in a solid-deuterium ($SD_2$) moderator at a low temperature (~ 6 K); some of them will be down-scattered so that they enter the storage volume in the ultra cold energy regime (≤ 250 neV). The operation of UCN in a pulsed mode makes it possible to keep the $SD_2$ at low temperatures despite the large power deposition during the beam pulse. The main purpose of the source will be to produce ultra cold neutrons to measure the electric dipole moment and the lifetime of the neutron. A detailed description of the source parameters can be found in reference [1].

For UCN a similar target system will be used as for the Spallation Neutron Source SINQ. The present SINQ target consists of an array of stainless steel tubes filled with lead and cooled by $D_2O$; it replaced an earlier design consisting of solid zircaloy rods in an identical geometric arrangement. The thermal and mechanical design of the SINQ target is described in References [2-5]. For the operation of UCN, it is foreseen to start with a solid zircaloy rod target, for which safe operation has been demonstrated in SINQ. In a second-generation target, lead filled zircaloy tubes will be used, which give a higher neutron flux than lead filled steel tubes [6].

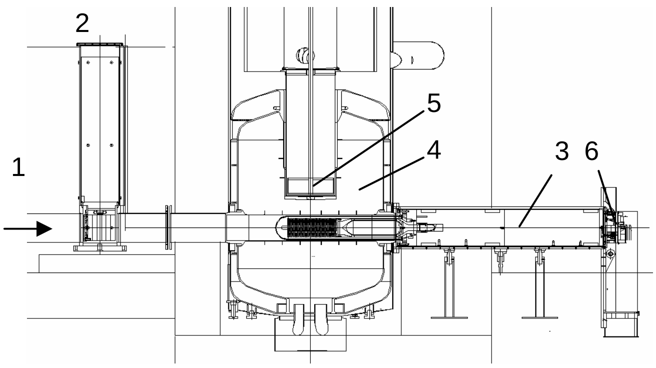


**Fig. 1:** Layout of the UCN source: 1 proton beam; 2: Collimator; 3: target shaft; 4: $D_2O$-moderator; 5: Solid $D_2$ moderator; 6: target head for coolant supply.

While SINQ is operated in a continuous mode, the UCN source will operate in a pulsed mode. Therefore, the thermo-mechanical behaviour of the zircaloy-clad Pb and the beam window has to be investigated.

## DESIGN OF THE TARGET SYSTEM

The target system for UCN is implemented as a horizontal insertion device (Fig. 1); it consists of an array of solid zircaloy rods (or lead filled zircaloy tubes), an aluminium-clad lead cylinder and an aluminium container with integrated beam window. The target array has a diameter of 210 mm and a length of 550 mm (Figs. 2, 3). A zircaloy tube has an outer diameter of 10.75 mm and a wall thickness of 0.75 mm. The pitch of the array is 12.75 mm. The relative amounts of the different materials in the target are 42.9 % Pb, 16.7 % Zr, 35.5 % $D_2O$ and 4.9 % void.

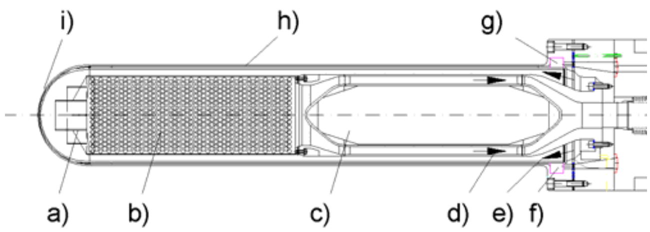


**Fig. 2:** Side view of the target; a) flow guides, b) array of solid zircaloy rods (or lead filled zircaloy tubes), c) aluminium-clad lead cylinder, d) outlet for the target coolant, e) inlet for the target coolant, f) inlet for the beam window coolant, g) outlet for the beam window coolant, h) target hull, i) beam window

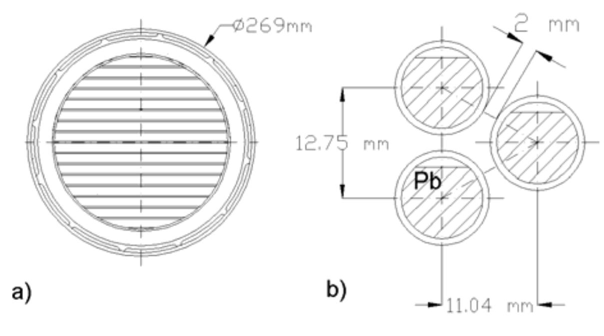


**Fig. 3:** Sectional views a) of the target and b) of the lead filled zircaloy tubes; the filling factor of Pb is ~90 % to allow for the expansion of the lead during heating and melting.

The distribution of the proton beam current density on the target will have radial symmetry and is given by a

Gaussian function with a standard deviation of $\sigma = 40$ mm; this will give a peak current density of 20 $\mu$A/cm$^2$ at the target centre for a proton beam intensity of 2 mA.

The beam diameter will be limited to a value of 200 mm by means of a collimator in front of the target. A beam loss of 4.4% is expected at the collimator. The high-energy neutrons, produced in the target, are shielded with the 50 cm long aluminium-clad lead cylinder and the 2 m long target shaft made of steel, to reduce activation and enable hands-on maintenance at the target head in case of target exchange.

**Cooling of the target array**

During the proton pulse, ~850 kW of the 1.2 MW beam power is deposited in the target array. The target array is cooled by a mass flow of 18 kg/s of $D_2O$, which gives a fluid velocity of 0.5 m/s in the empty bed and of 3.2 m/s in the gap between the tubes. For the zircaloy tubes of the target array a film heat transfer coefficient of $2.5 \cdot 10^4$ W/m$^2$/°C has been evaluated from the formalism of ref. [7]. Two cylindrical flow guides suppress the formation of vortices in the entrance region of the target (Fig. 4). The FLOTRAN computational fluid dynamic option of ANSYS [8] has been used for the calculation of the fluid flow in a rotational symmetric finite element model. For this calculation the target array has been modeled as an isotropically distributed resistance.

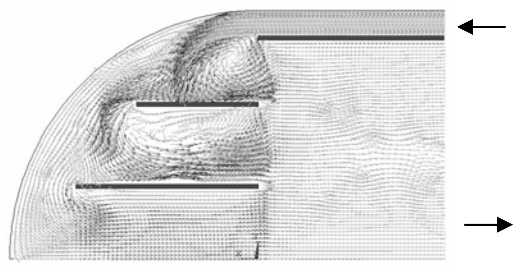

**Fig. 4**: Plot of the distribution of the fluid velocity in the target entrance region. The formation of large vortices is suppressed by the insertion of two cylindrical flow guides.

**The target hull and the beam window**

The target hull consists of two concentric aluminum (AlMg3) shells with $D_2O$ flowing in between (Fig. 5). The spherical section forms the beam window. The outer diameter of the target hull and the spherical window is 269 mm. The thickness of each window is 2.5 mm at the beam center and increases to 5 mm at the connection of the spherical and cylindrical part of the target hull. The gap between the two windows has a uniform width of 2 mm. The introduction of a flow guide at each side of the inner window – as can be seen in Fig. 5 and 6 - results in a more uniform distribution of the fluid velocity across the beam window.

A CFD-analysis using FLOTRAN has been performed to calculate the thermo-hydraulic parameters of the beam window. The fluid velocity in the beam region is $\geq$ 2.5 m/s for a total mass flow of 2.5 kg/s of $D_2O$ (Fig. 6).

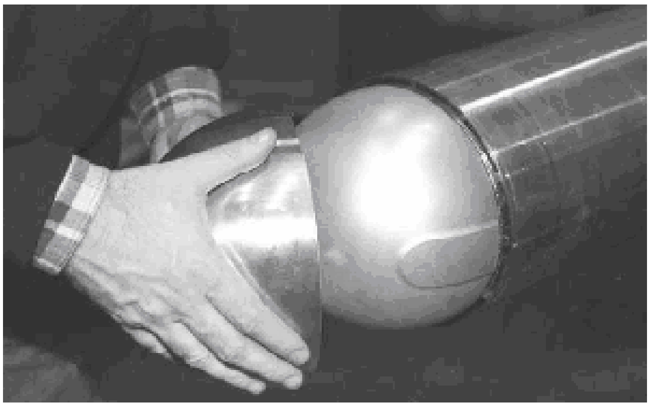

**Fig. 5:** The picture shows the SINQ target hull, which is similar to the UCN target hull, before welding of the outer beam window.

For a fluid velocity of 2.5 m/s, a $D_2O$ bulk temperature of 40$^o$ C, a static pressure of 0.5 MPa and a saturation temperature of 150$^o$ C, the forced convection regime allows a heat flux of up to 1.9 MW/m$^2$ from the window surface. This corresponds in the case of a 2.5 mm thick aluminum window, to a proton current density of 100 $\mu$A/cm$^2$. Above 1.9 MW/m$^2$ subcooled boiling occurs, which enhances the heat transfer (Fig. 7). The film heat transfer coefficient in the forced convection regime is derived from the formalism of ref. [7]. For the subcooled boiling regime, the Shah-correlation [9] has been used to evaluate the heat transfer.

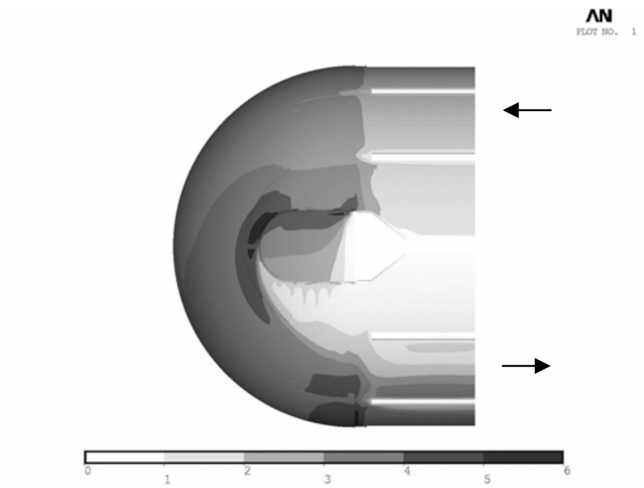


**Fig. 6:** Contour plot of the calculated fluid velocity [m/s] at the beam window for a total mass flow of 2.5 kg/s of $D_2O$. The arrows indicate the flow direction.

The critical heat flux (burn out) has been estimated from the empirical formula given by S. Mirshak [10]. The burn out is expected at a heat flux of $q \cong 7.7$ MW/m$^2$, which corresponds to a peak proton current density of ~ 400 $\mu$A/cm$^2$. During normal operation conditions of the UCN target the peak proton density does not exceed 20 $\mu$A/cm$^2$ for a proton beam current of 2 mA.

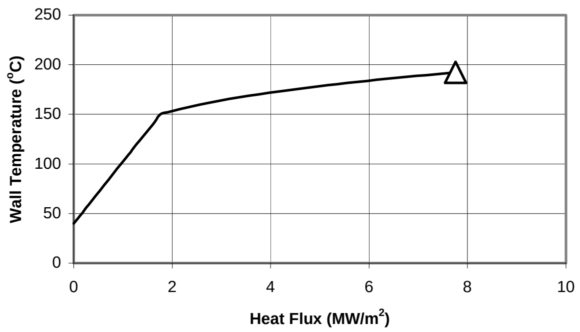


**Fig. 7:** Wall temperature of the window as a function of the heat flux. (Bulk temperature 40°C, static pressure 0.5 MPa, fluid velocity 2.5 m/s). The triangle indicates the critical heat flux (burn out).

A FE-analysis using ANSYS [8] has been performed with an axially symmetric model to calculate the temperature and stress distribution within the window material. In Fig. 8 the temperature response of the outer beam window has been plotted as function of time.

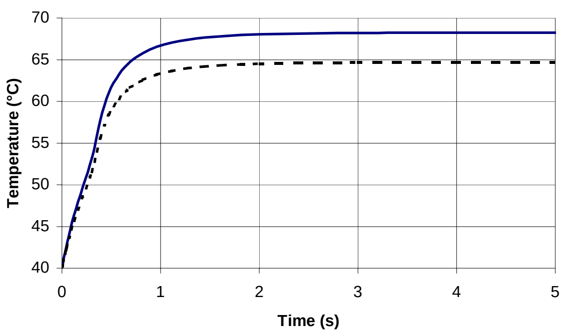


**Fig. 8:** Temperature response of the outer beam window at its center for a peak current density of 20 μA/cm² as a function of time (dashed line: $D_2O$-side; solid line: vacuum side).

One can see from Fig. 8 that the temperature rises to a maximum of 65°C at the cooled side and of 68°C at the vacuum side of the outer beam window in a time span of approximately 2 s. This temperature change induces a cyclic stress component $S_t$ within the window material. In addition the aluminum beam window is subject to a static stress component $S_p$, which is caused by the pressure load of the coolant (Fig. 9). The resulting stress $S_p$+$S_t$ reaches 17 N/mm², which corresponds to a safety factor of 4, based upon the yield strength (~ 70 N/mm²) of the used window material AlMg3.

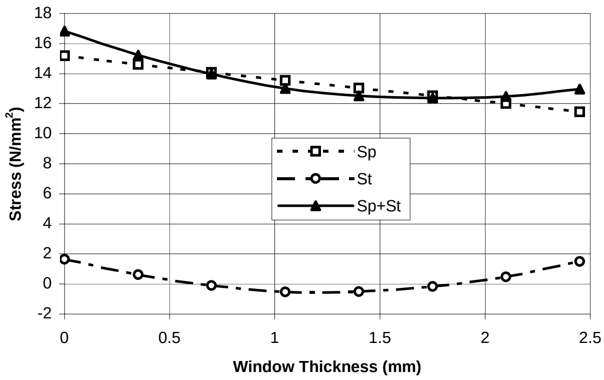


**Fig. 9:** Calculated stresses at beam center in the outer beam window for a coolant pressure of 0.5 MPa and a peak current density of 20 μA/cm². (Sp: pressure load only, no beam; St: beam on, no pressure; Sp+St: with pressure, beam on.)

### Lead filled zircaloy tubes

The design of the target tubes has to fulfill demands of a high corrosion resistance of the wetted material (which is given for zircaloy-clad lead) and a high integrity of the cladding with respect to stress cycling. The stress cycling is caused by the thermal expansion of the lead over the duration of the proton pulses. The temperature response of the lead and the stress of the cladding depend on the thermo-mechanical contact between the lead and the zircaloy. Recent measurements of the temperature response of some lead-filled stainless-steel tubes of the target in operation in SINQ show, that the heat contact increases after a few days of operation to a nearly perfect connection between the lead and the stainless-steel wall. Therefore, the stress of the zircaloy cladding has been calculated for the following two cases: I) no heat transfer and sliding mechanical contact between the lead and the zircaloy, II) perfect intermetallic connection. During operation a maximum heat load of 440 W/cm³ is expected in the lead filled zircaloy tubes. The temperature response of the lead is shown in figure 10 for case I) and II). The temperature rise is about 300°C/s, which corresponds to a maximum strain amplitude of 0.01 up to melting and to a strain rate of 0.01 $s^{-1}$ of the lead. For case I), the lead temperature will increase to the melting point in ~1 s. Because of the high homologous temperature (0.5 to 0.9) the plastic deformation behavior of the lead is strongly temperature and strain-rate dependent. In order to simulate the stress response of the zircaloy cladding with FE techniques, tension tests of lead were performed at temperatures of 20, 100 and 150 °C for a strain rate of 0.01 $s^{-1}$ [11]. Fig. 11 shows the measured stress-strain relations. The values for 300 °C have been extrapolated with the relationship $\sigma = A \cdot \exp(-B \cdot T)$ from the values measured at lower temperatures (see [12]). A and B are material-dependent constants and T is the temperature.

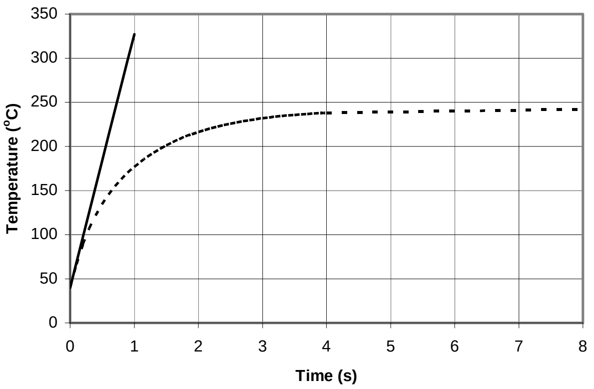


**Fig. 10:** Temperature response of lead due to the heat load by the proton pulse. (solid line: case I); dashed line: case II)).

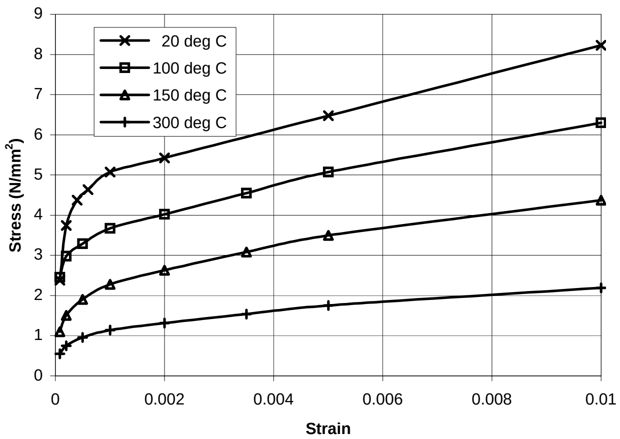


**Fig. 11:** Measured stress-strain relations for lead at temperatures of 20, 100 and 150 °C for a strain rate of 0.01 $s^{-1}$. The values for 300 °C have been extrapolated from the values measured at lower temperatures.

The calculated time-dependent temperature response of lead and the measured stress-strain relations of figure 11 have finally been used to simulate the stress response of the zircaloy cladding during the proton pulse (Fig. 12). For case I), the stress of the cladding reaches a maximum value of ~110 N/mm$^2$. For case II), the stress of the cladding reaches about 190 N/mm$^2$. An investigation of the fatigue behavior of zircaloy-2 shows, that the fatigue limit (for $10^6$ cycles) was 235 N/mm$^2$ at 20°C and 190 N/mm$^2$ at 300°C [13]. For case I), the temperature of the cladding material is 50°C and for the case II), 85°C. Therefore no cyclic fatigue will be expected for the zircaloy cladding due to the pulsed operation in UCN.

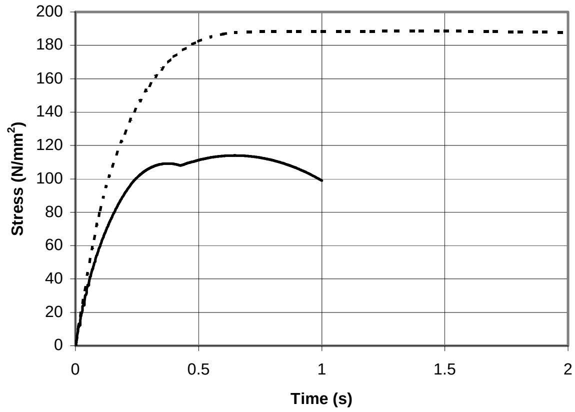


**Fig. 12:** Calculated stress response of the zircaloy cladding as a function of time; solid line: case I); dashed line: case II).

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