THERMO-MECHANICAL ASSESSMENT OF THE DISK TARGET CONCEPT FOR THE SPALLATION NEUTRON SOURCE IN THE BASQUE COUNTRY

J. Wolters [a,*]; F.Albisu [b]; G.S. Bauer [a]; M. Butzek [a]; D. Filges [a]; G. Hansen [a]; F. Legarda [c]; S. Martin [a]; K. Nünighoff [a]; M. Tello [d]

[a] *Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Strasse, 52425 Jülich, Germany*
[b] *SENER Bilbao, AVDA. Zugazarte 56, 48930 Las Arenas, Spain*
[c] *Universidad del País Vasco (UPV), Dep. de Ingeniería Nuclear y Mecánica de Fluidos, Alda. Urquijo, s/n., 48013 Bilbao, Spain*
[d] *Universidad del País Vasco (UPV), Facultad de Cienca y Tecnologia, Apdo. 644, 48080 Bilbao, Spain*

[*] *j.wolters@fz-juelich.de*

In a quest to improve the scientific infrastructure in the Bilbao region, the Basque Administration entrusted a group of Professors of the University of the Basque Country together with SENER with proposing a concept for a large research facility. This group, in collaboration with Forschungszentrum Jülich GmbH (FZJ), worked out the proposal for a regional spallation neutron source. The initial beam power level was chosen as 250 kW$_b$ in order to be competitive on a European level, but still allowing a cost effective design.

For the proposed concept of a disc shaped solid spallation target, details of the thermo-mechanical behavior were studied by the design group of the Central Department of Technology at FZJ. These investigations show that a stationary target is capable of coping with the heat deposited by the proton beam of 250 kW$_b$, provided certain measures are taken to ensure sufficient cooling and to avoid excessive local stresses. The heat removal capacity of the target can be significantly increased by operating it with a continuous rotation at a very moderate revolution rate of a few turns per minute, which will allow an increase of the beam power to 500 kW$_b$ or beyond.

I. INTRODUCTION

In a first assessment [1] a concept was worked out for a spallation neutron source of regional (Europe-wide) competitiveness to be built in the Basque Country as a new research facility. The initial beam power level was chosen at 250 kW$_b$ in order to be competitive with the two presently existing but slowly aging leading neutron sources in Europe, ISIS (UK) with a beam power of 160 kW$_b$, and the ILL high flux reactor in Grenoble (F). Given the cost frame of some M€ 300 (which is extremely low for a facility of this kind), emphasis was placed on minimizing initial investment and operational cost, in addition to satisfying known users' requests in the best possible way. This resulted in two very important features of the proposed concept:

• A circular accelerator (synchrotron), in which the desired proton beam power can be reached by choosing a reasonably high proton energy of 2 GeV and a relatively modest average beam current of 125 µA. This allows keeping the injection energy at 50 MeV and thus building a relatively compact linac (whose final energy is known to be a cost driver in every accelerator concept). The option to increase the beam power at a later stage if more funds become available, is still open by increasing the injection energy and therefore the space charge limit for the injected current. For instance, rising the injection energy to 400 MeV with a new linac would allow operating the facility at 1 MW$_b$ at 50 Hz, the same level as the new world leading SNS in the USA, which is just undergoing its commissioning phase.

• A disk shaped target made of tungsten that can be rotated to reduce radiation damage, which would serve the facility for at least 30 years without the need for exchange. The proposed diameter of the target disk is 50 cm and the height is 5 cm (cp. Fig. 1).

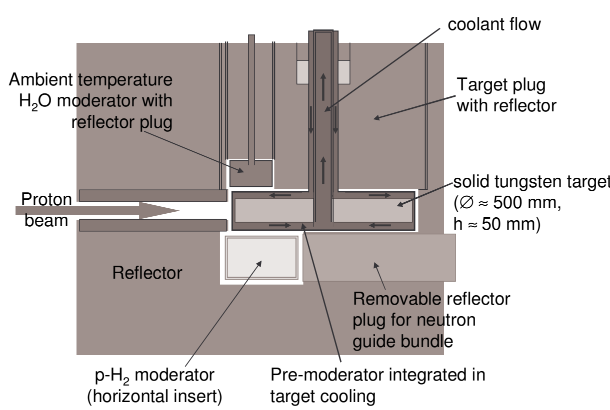

Fig. 1: Proposed target concept for the spallation neutron source in the Basque Country

This very novel target concept could not be investigated in depth in the first study. In particular, details of the thermo-mechanical behavior and optimization of heat removal were not looked at. For this reason the FZJ design team was charged with the second study of limited scale -presented here- in order to add some more depth to these questions and at the same time, assess whether the same target concept can be used if the beam power were to be increased to 500 kW_b or beyond.

II. MONTE-CARLO SIMULATION OF THE ENERGY DEPOSITION INSIDE THE TARGET AND EXPECTED NEUTRONIC PERFORMANCE

The main boundary condition for the thermo-mechanical design of the solid target is the heat deposition inside the target. At the beginning of the second study no detailed nucleonics analysis for the tungsten target using 2 GeV protons was available. Hence, in a first approach conservative assumptions were made with respect to heat generation. It was assumed that the total heat generation in the target is 60 % of the beam power. With respect to the axial profile of the energy deposition, the AUSTRON profile [2] was taken, which had been determined for 1.6 GeV protons in tungsten. Its abscissa was rescaled using the stopping lengths of protons at 1.6 GeV and 2.0 GeV to allow for protons at higher energies (cp. Fig. 4).

The precise Monte-Carlo simulation, which was performed in order to qualify the simplified approach with respect to the energy deposition, is presented in the following.

II.A. Energy Deposition in Solid Tungsten Target

Monte-Carlo simulations of the projected target station have been performed using the MCNPX code system [3]. A simplified geometry model of the target station was used. The main parts of the geometry are the tungsten target wheel with a diameter of 50 cm and a height of 5 cm, the surrounding lead reflector with diameter and height of 100 cm and two moderators. A thermal moderator in a rectangular aluminum container with a volume of 12x15x5 cm^3 was located above the target and a cryogenic para hydrogen moderator at T = 20 K in a cylindrical aluminum container (radius 7.5 cm, height 12 cm) was installed below the target. The midpoints of both moderators are at distance of 10 cm from the target shell. A vertical cut through the mid-plane of the geometry is shown in Fig. 2.

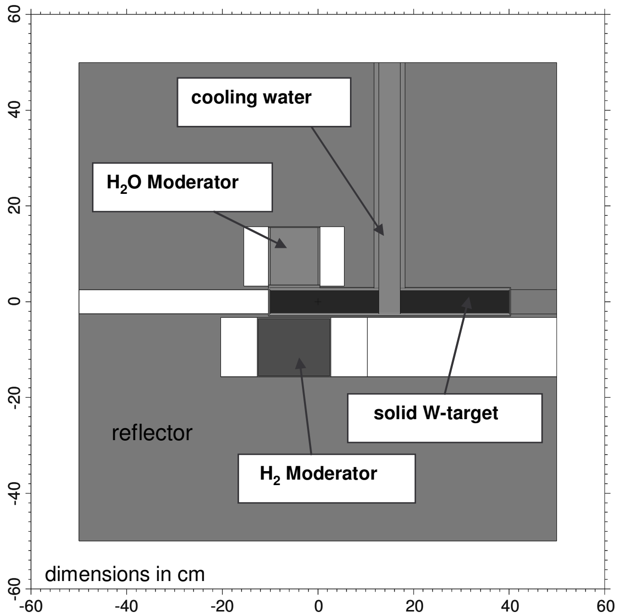

Fig. 2. Vertical cut through the geometry model used in MCNPX for simulating the energy deposition and neutron spectra. Dimensions are in cm.

The energy deposition due to the interaction of the primary proton beam with the solid tungsten target was simulated to determine the total power deposited inside the whole target. Additionally the contributions from different particles were disentangled. In order to investigate the spatial distribution of the energy deposition simulations using a mesh tally were carried out. Especially for the spatial distribution of the energy deposition a proper description of the elliptical beam profile and the parabolic intensity distribution is mandatory. For the simulations an elliptical footprint with the two radii r_x = 10 cm and r_y = 1.5 cm were used. The kinetic energy of the incident protons was 2.0 GeV and the results were normalized to the beam power of 250 kW_b. The resulting energy deposition in the mid-plane of the target is shown in Fig. 3.

More details can be seen by plotting a projection of the 3D results on the proton beam axis. Fig. 4 shows the time averaged energy deposition along the proton beam axis. The dip between 23 cm and 27 cm is due to the cooling water pipe, where less energy is deposited compared to tungsten. The solid line represents a fit through the simulated data. A maximum value of about 350 MW/m^3 can be observed at a target depth of approximately 2 cm. The energy deposition assumed for the thermo-mechanical investigations on the target is also shown in Fig. 4. The maximum value was 370 MW/m^3 at a target depth of 3 cm.

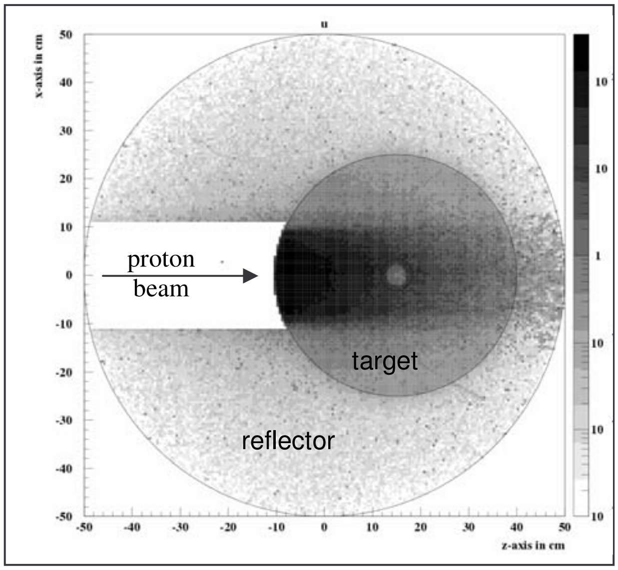

Fig. 3. Spatial distribution of the time averaged power deposited in the mid-plane of the tungsten target. The spot in the center of the target marks the cooling water tube. The energy deposition is given in MW/m^3.

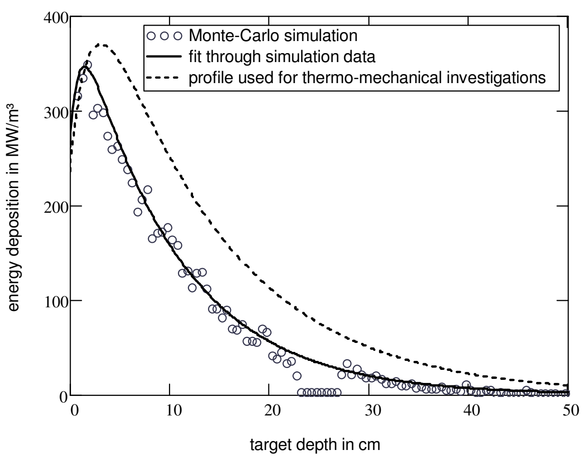

Fig. 4. Time averaged energy deposition along the proton beam axis.

The total energy deposition was determined to be about 99 kW, i.e. 39.5 % of the total beam power, which is much less then the assumed value of 60 %. The main contributors to the energy deposition are protons (55 %) and photons (21 %). A more detailed overview is given in Tab. I.

TABLE I. Energy deposition by particle type

Particle	Energy deposition in kW	Relative to beam power of 250 kW
Proton	54.43	21.77 %
Neutron	0.40	0.16 %
Photon	21.16	8.47 %
Deuteron	2.84	1.13 %
Triton	2.20	0.88 %
^{3}He	0.44	0.18 %
^{4}He	11.70	4.68 %
π^+ and π^-	5.50	2.20 %
π^0	0.10	0.04 %
Σ	**98.76**	**39.5 %**

II.B. Expected Thermal and Cold Neutron Spectra

In addition to the energy deposition the neutronic performance of the generic moderators has been investigated. The energy (and lethargy) spectra of the thermal water moderator (T = 293 K) and the cold para hydrogen moderator (T = 20 K) were determined with a point detector at a distance of 500 cm from the moderator surface. The spectra are normalized to the number of protons per pulse, the solid angle and the width of the energy (or lethargy) bins. The resulting spectra are shown in Fig. 5.

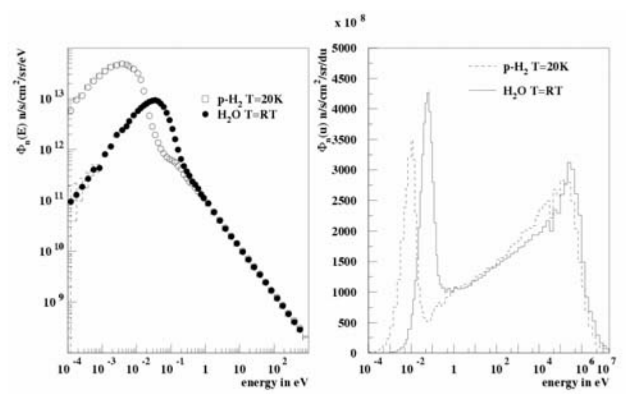

Fig. 5. Energy spectra (left histogram) and lethargy spectra (right histogram) of a water moderator at room temperature and a cold para hydrogen moderator operated at T = 20 K.

The energy spectra of both moderators show the expected behavior. The 1/E-slope for energies above 1 eV as well as the maximum in the thermal and sub-thermal energy range can be seen. The lethargy spectrum of para hydrogen illustrates the way neutrons are shifted towards lower energies compared to the spectrum of the thermal water moderator. The total flux of thermal and sub-thermal neutrons (E_n<0.413 eV) is about $9.4 \cdot 10^{11}$ n/s/cm^2/sr for both moderator types. This value scales fairly well with earlier results obtained for the optimized 5 MW ESS configuration with a mercury target [4].

It should be noted that no attempt has been made so far to optimize the present configuration. Experience shows that up to 50% increase or more can be obtained during such a procedure.

III. FINITE ELEMENT CALCULATIONS ON THE THERMO-MECHANICAL BEHAVIOR OF THE TARGET

III.A. Basics of Numerical Investigations

The numerical investigations with respect to the thermo-mechanical behavior and the heat removal capacity of the proposed target concept were performed with the commercial finite element code ANSYS [5].

Two different geometrical models were used for the investigations. First, for a simplified monolithic circular solid target the main effects of heat removal were studied. Due to high thermal stresses that would occur for such a monolithic target a more detailed segmented target model was developed to study the thermo-mechanical behavior. This model consists of a solid disk in the center and involute shaped segments at the periphery (cp. Fig. 6). The advantage of involute shaped segments - and consequently involute shaped cooling channels on the surfaces - is that the efficiency of the cooling will not depend on the radial position. The distance between the cooling channels perpendicular to the coolant flow and the velocity of the coolant flow will not change while approaching the outer edge of the target (cp. Fig. 7). For the upper and lower half of the target the segments can be arranged in opposite directions and can be held together by bolts (tie-rods). With respect to stress reduction, the disk in the target center should also be split through its mid plane and kept together by bolts. The cooling water duct in the center of the target was neglected in the study.

Cooling channels, which will follow the involute shape of the segments on the upper and lower surface of the target, were neglected in the simplified model. However, their effect was taken into account by using an effective heat transfer coefficient which is about 2.8 times higher than the actual coefficient on the surfaces of the channels (cp. Fig. 8). Cooling of the side surface of the target was neglected in the study. A constant coolant temperature of 20 °C was assumed for all calculation.

For tungsten, temperature-dependent material properties were used in the calculations. This is important particularly with regard to the thermal conductivity [6].

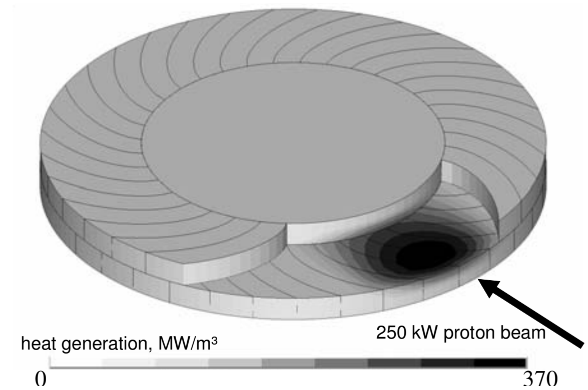

Fig. 6. Heat generation inside the segmented target for a 250 kW proton beam (pessimistically assumed to be 150 kW_{th}) and an elliptical footprint with the two radii $r_x = 10$ cm and $r_y = 1.5$ cm. A parabolic intensity distribution within the footprint was assumed.

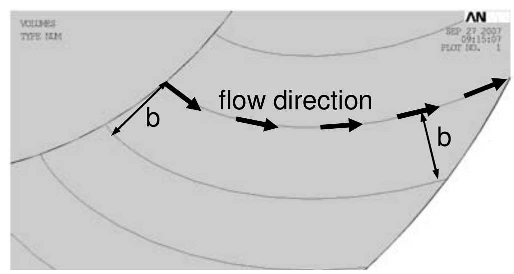

Fig. 7. Involute shaped segments have a constant thickness perpendicular to the flow direction.

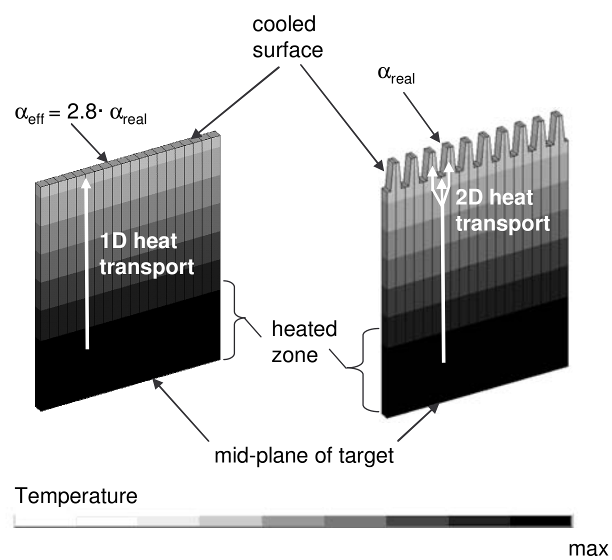

Fig. 8. A two-dimensional model was used to assess the heat transfer at the cooled surfaces of the segments. The effective heat transfer coefficient for the simplified flat surface (left side) was adjusted such that the same temperature distribution is achieved compared with the more detailed model (right side).

III.B. Results for a Stationary Target at 250 kW beam power

The calculated stationary temperature distribution inside a monolithic solid tungsten target is shown in Fig. 9. An effective heat transfer coefficient α_{eff} = 20000 W/(m²K) was applied at the upper and lower surface of the target, which will correspond to a coefficient of about 7200 W/(m²K) for a grooved surface. This value is easily achievable for moderate cooling water flow velocities.

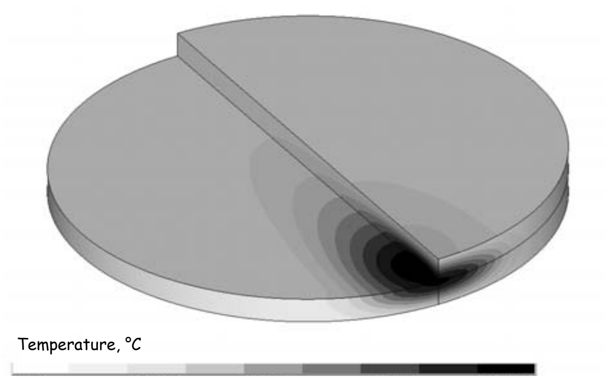

Fig. 9. Stationary temperature distribution inside a monolithic solid tungsten target

III.B.1. Transient Effects

The effect of a pulsed proton beam at 50 Hz was investigated, considering a short pulse of a few microseconds. Due to this short time scale each pulse will quasi instantaneously increase the local temperature. For the zone of maximum heat deposition the corresponding temperature increment per pulse is slightly less than 3 K. During heating-up the temperature increments of the first pulses are just accumulated because the characteristic thermal diffusion time constant of about 2.2 sec (at 20 °C) is large compared to the pulse interval. With increasing local temperatures the effect of heat conduction will increase and once the quasi-stationary state is reached, the deposited heat of one pulse is removed again in-between two pulses. Compared to the maximum quasi-stationary target temperature of about 617 °C the temperature increment of 3 K due to one pulse is quite small and therefore the pulsed operation is not important for the thermo-mechanical design. For further investigations it is sufficient to considering a time-averaged heat generation.

Transient effect for the stages of heating-up and cooling-down the target are shown in Fig. 10. The corresponding calculations were done for an initial target temperature of 20 °C and 100 s of heating-up and cooling-down periods, respectively. As can be seen from Fig. 10 the heat capacity of the target is quite high compared to the energy deposition, so it takes several seconds to approach equilibrium temperature in the target.

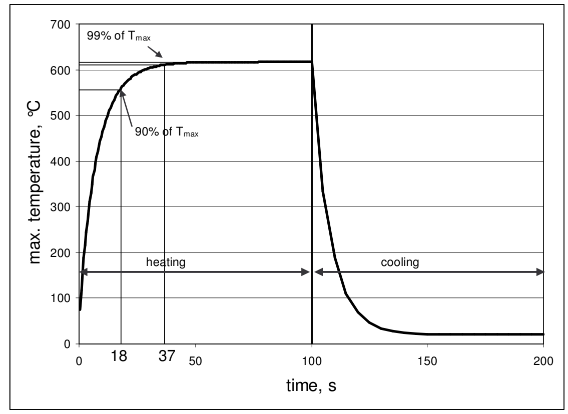

Fig. 10. Maximum temperature inside the target as a function of time for 100 s of heating-up and 100 s of cooling-down

III.B.2.Geometrical Aspects

Several calculations were performed with respect to the target geometry and the beam footprint. The results will not be shown in detail but will be briefly summarized:

• Calculations on the influence of the target diameter have shown that, due to the predominantly vertical heat flux towards the actively cooled upper and lower surfaces, the maximum temperatures do not depend significantly on the diameter of the target. The additional surface available for cooling cannot be used effectively because of the low temperatures in this region. The stresses inside the target will slightly increase by enlarging the target diameter. This is caused by the higher stiffness of the colder surroundings, which will restrain the thermal strains in the heated zone of the target.

• In contrast to the diameter, the target height influences the temperature inside the target significantly. A certain heat flux in vertical direction involves a corresponding temperature gradient. If the target thickness is increased, the maximum temperatures in the centre will increase approximately by the temperature gradient at the surface multiplied by half of the thickness increase. The stresses will also rise due to a higher target thickness.

• The beam width also has a significant influence on temperatures. By increasing the beam width, the peak heat generation is reduced and the energy deposition profile perpendicular to the main vertical heat flux is flattened. This will also significantly decrease thermal stresses within the target.

• The energy deposition profile in vertical direction is less important for the temperature distribution. Due to the almost vertical heat flux within the flat target, the surface heat flux –and therefore also the surface temperature– will not depend significantly on the exact vertical distribution of the heat generation but only on the total heat generated below the surface region considered. With respect to the maximum temperature inside the target a smoother distribution is advantageous, because it results in a reduced heat flux –and hence a reduced temperature gradient– within the heated region of the target. This will also reduce stresses inside the target.

III.B.3 Results for a Segmented Target

A typical model of the segmented target is shown in Fig. 6. To allow for thermal strains, small gaps can be left between the single segments. These gaps will disturb the circumferential – and in parts also the radial - heat transport and will therefore influence the calculated temperatures, although the dominant heat flux is in vertical direction. For the case where the heat transport between the single parts of the target is completely neglected the influence of segments on the maximum target temperature is shown in Fig. 11. Compared to the monolithic target the maximum temperature will increase by about 10 % if a fine segmentation is used.

The stresses can be reduced significantly by using a segmented target. In Fig. 12 the stress distribution is shown for a monolithic and for a segmented target (in this case the central plate is additionally split through its mid plane). While for the monolithic target the stress level exceeds the yield stress of the unirradiated material, the stress level within the segmented target is such that plastic deformations can be avoided (depending on the tungsten composition and delivery condition).

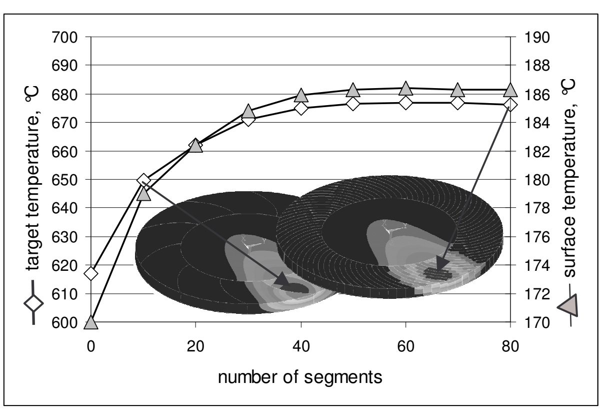

Fig. 11. Maximum temperature inside the target and at the cooled surface of the target as a function of the number of segments.

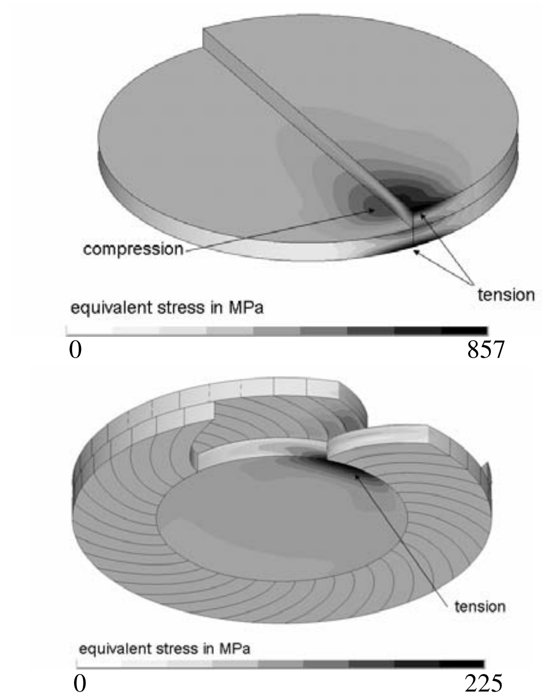

Fig. 12. Stress distribution within a monolithic solid target and within a segmented target. Due to the segmentation secondary stresses can be reduced significantly.

III.C. Results for a Rotating Target

Calculations carried out as described above have shown that with the concept of a stationary disk shaped tungsten target, it is possible to remove the heat generated by a beam of 250 kW_b power in the target material, if suitable provisions -such as segments- are made to limit the stress inside the target. Dealing with the question whether operating at 500 kW_b or above is possible for the same target, it is obvious that a more evenly distributed heat over the target circumference would make things much easier. This can be achieved by continuous rotation of the target during operation.

As indicated in section III.B.1 (cf. Fig. 10), the temperature rise is comparatively moderate at the start-up. There is sufficient time for moving the hot zones of the target away from the main beam axis by a slow continuous rotation. In order to avoid high temperatures in the centre of the target, a lateral beam offset can be used in addition. These aspects were investigated in detail by additional transient calculations.

In Fig. 13 the quasi-stationary temperature distribution is shown for a rotational frequency of 6 rpm or 0.1 Hz. By applying a continuous rotation the temperature inside the target can be reduced by a factor of about 5. The maximum equivalent stress is reduced from 225 MPa to about 33 MPa in this case.

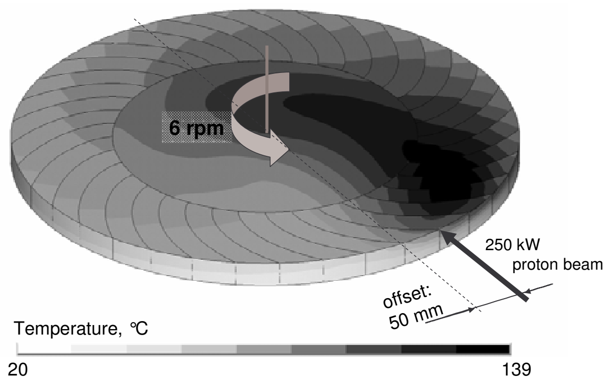

Fig. 13. Temperature distribution within a rotating segmented target. Due to the rotation a more even temperature distribution at low level is achieved.

In Fig. 14 the maximum target temperatures for the rotating target are shown as a function of the beam power. For a beam power of 1 MW_b the maximum temperatures are even lower than for a stationary target at 250 kW_b. If the target is rotated twice as fast (12 rpm instead of 6 rpm), the maximum target temperature can be further reduced from 520 °C to about 413 °C. It should also be mentioned that –in contrast to the stationary target– a larger target diameter will also decrease temperatures correspondingly for a rotating target.

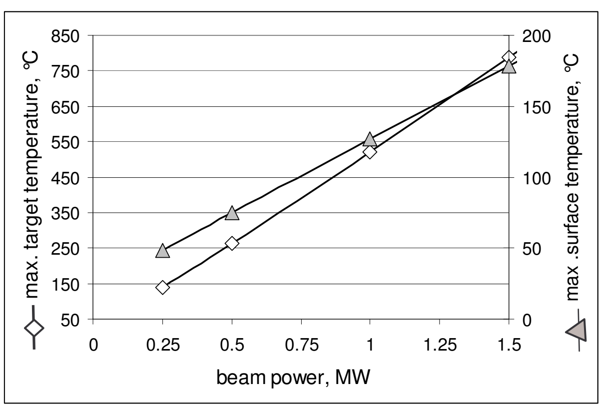

Fig. 14. Temperatures within a rotating segmented target as a function of the beam power at 6 rpm.

IV. CONCLUSIONS

The main results can be briefly summarized as follows:

• The target, if operated in a stationary mode (i.e. without continuous rotation) is capable of dissipating the heat deposited in its volume by the proton beam of 250 kW_b (pessimistically assumed to be 150 kW_{th}), provided certain measures are taken to ensure sufficient coolant flow at the position of maximum heat flux and a subdivision is introduced in the target material to avoid excessive local stress. Expanding the beam will help to reduce the heat removal problem for a stationary target.

• The heat removal capacity of the target can be significantly increased by operating it with continuous rotation at a very moderate revolution rate of a few turns per minute.

• In view of the possible later increase in beam power it is recommended to design the target system such that continuous rotation of the target is possible from the very beginning. This simplifies substantially the heat removal from the target surface and reduces internal stresses to rather low levels, while at the same time allowing a reduction of the coolant flow. The latter leads to a higher temperature rise in the coolant and makes smaller heat exchangers feasible. The savings that result for the coolant loop from this are estimated (without detailed considerations) to more than offset for the extra cost of a target drive mechanism and rotating seal.

It should be noted that continuous rotation is also likely to further increase the target life time at a given level of beam power because the distribution of radiation damage over the circumference is more even and the peak stresses -eventually leading to fatigue- are much lower than in the case of intermittent change of the point of incidence of the proton beam (stationary operation) where beam trips result in very serious temperature transients.

REFERENCES

1. Michael Butzek, G.S. Bauer, D. Filges, G. Hansen, S. Martin, *"Suggestions for the Accelerator and Target System for the Spanish Spallation Neutron Source for the Basque Country"*, Forschungszentrum Jülich GmbH, D-52425 Jülich (2005).
2. P. Bryant, M. Regler, M. Schuster (editors), "The AUSTRON Feasibility Study" , Austrian Ministry for Science and Research, Vienna (1994).
3. H.G. HUGHES et al., "MCNPX-The LAHET/MCNP Code Merger", X-Division Research Note XTM-RN(U)97-012, LA-UR-97-4891, Los Alamos National Laboratory (1997).
4. ESS Council, "*The ESS project, Volume III: Technical Report"*, May 2002, ISBN 3-89336-303-3
5. ANSYS, Release 10.0, ANSYS Inc., 2006
6. C.Y. Ho, R.W. Powell and P.E. Liley, *J. Phys. Chem. Ref. Data*, v1, p279 (1972)