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Rotating solid target for 5 MW and beyond

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ABSTRACT

One of the alternative target options for ESS to be evaluated is a rotating solid target. Between 2005 and 2007 the Forschungszentrum Juelich has worked on a study for a rotating tungsten target system for a proposed regional spallation neutron source in the Basque country. Based on this work we have evaluated the feasibility of a rotating target for 5 MW and beyond. Beside thermal calculations for this target we will present a concept to fit this target into the existing ESS target station design.

1. Introduction

During the recent redesign phase of ESS alternative target concepts are discussed. Beside mercury this includes LBE (lead bismuth eutectic), probably LGE (lead gold eutectic) and a solid rotating target with tungsten as candidate material. Although the solid rotating target was regarded to be the backup solution during the ESS design phase, up to 2003 no serious work has been done at that time to design and calculate such a target. During the SNQ concept phase in the early 1980th a solid rotating target with tungsten and even uranium as target material was discussed for a beam power up to 5.5 MW and heat removal capacities up to 12 MW at 100 Hz repetition rate [1][2]. Therefore it was assumed that such a target should be feasible for ESS too. Between 2005 and 2006 Juelich has worked on a study for a smaller scaled spallation source for the Basque country in Spain. For this source with a proton beam power of 250 kW – 500 kW a small rotating edge cooled tungsten target was considered [3]. Within the work presented here both concepts (edge cooled and SNQ-type) should be evaluated concerning the heat removal capacities for ESS relevant conditions. It will be shown what effects are governing the limits for both design approaches. The results of this work can be used to design and optimize a solid rotating target for multi megawatt spallation sources.

2. Target material and cladding issues

Looking into existing sources using solid target material, tungsten (ISIS) and lead (SINQ) have been chosen. Although the expected neutronic performance for both materials is good, a suitable cladding is necessary to avoid direct contact between the cooling water and the target material. State of the art for the cladding for both sources is:

- Tungsten clad by a layer of tantalum using HIP (e.g. ISIS)
- Lead clad by zircaloy pipe (i.e. SINQ)

For SNQ it was proposed to shrink tungsten into an aluminium or zircaloy pipe.

As a combination of the proven SINQ design and the SNQ design it is proposed to use a pipe-shaped zircaloy cladding with tungsten core. The gap between the outer diameter of the tungsten and the inner diameter of the pipe will be filled with lead or another metal with a low melting point. This concept bases on the proven SINQ design but uses tungsten in the core of the pin in order to increase the average target material density over the SINQ cannelloni design and thus trends to increase the neutronic performance.

For tungsten the following design limiting temperatures are assumed:

- Tungsten/steam reaction above 800°C
- Tungsten/air reaction above 500°C
- Cladding needed to avoid direct contact between tungsten and cooling water in normal operation.
- Assuming a possible cladding failure the water cooled surface temperature should stay below 700°C.
- Temperature of potentially exposed surfaces in the event of a loss of confinement should stay below 500°C

Therefore for the calculations in this paper it is assumed that the maximum mean temperature (disregarding the pulse) in the tungsten should not exceed 500°C.

3. Heat load due to the beam

The major parameter for the thermal design of the target is the heat load by the beam. Unfortunately reliable MCNPX data for tungsten under ESS-like conditions were not available. Therefore data produced for the AUSTRON concept study that were available for a proton energy of 1.6 GeV were scaled by the stopping power of tungsten for 1.33GeV and 2 GeV for comparison [3]. Although these heat loads still need to be confirmed, their use allows studying different phenomena relevant for the heat removal capacity of a solid rotating target. In the meantime, MCNPC calculations conducted for the study on the 2nd target station for SNS (ORNL) lead to the assumption that at least the scaled data for 1.33 GeV is over conservative. Figure 1 shows the heat load distribution for tungsten for 1.33 and 2 GeV as used for the calculations within this paper. For comparison the heat load distribution for Hg and LBE are also shown.

Another point of discussion was the expected beam profile. Although a parabolic beam profile would be favourable, from the point of view of beam dynamics a Gaussian distribution seems to be more realistic. In order to keep the same maximum, a Gaussian distribution with 2 sigma within the nominal beam footprint ($\kappa = 2$) would be necessary. This would in return leave 13% of the beam power outside of the footprint. In order to get as much as possible (~99%) of the beam inside of the nominal footprint, $\kappa = 3$ would be necessary. This would result in an increase of the peak heat load by a factor of 2.25. Figure 2 shows the different distributions.

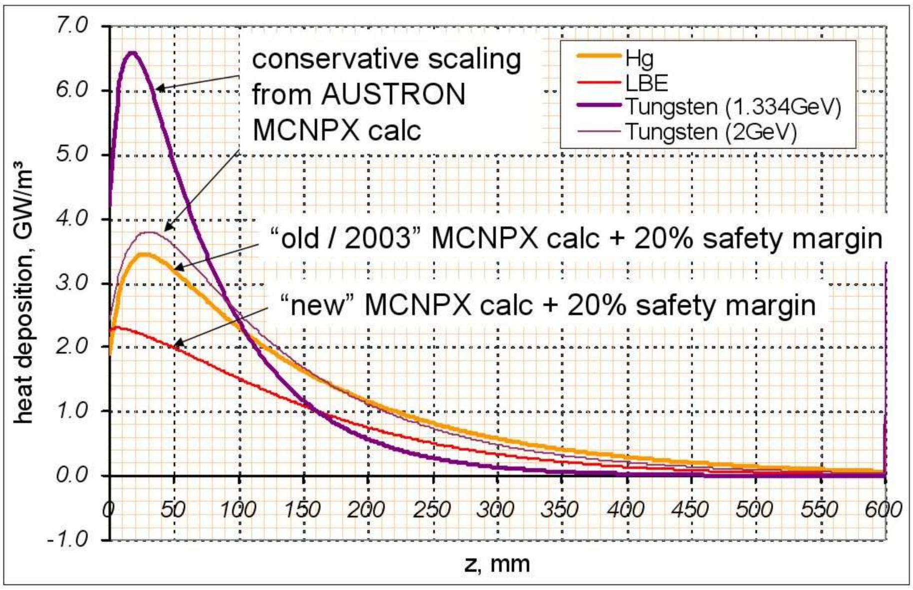

Figure 1: Heat load distribution along the beam axis.

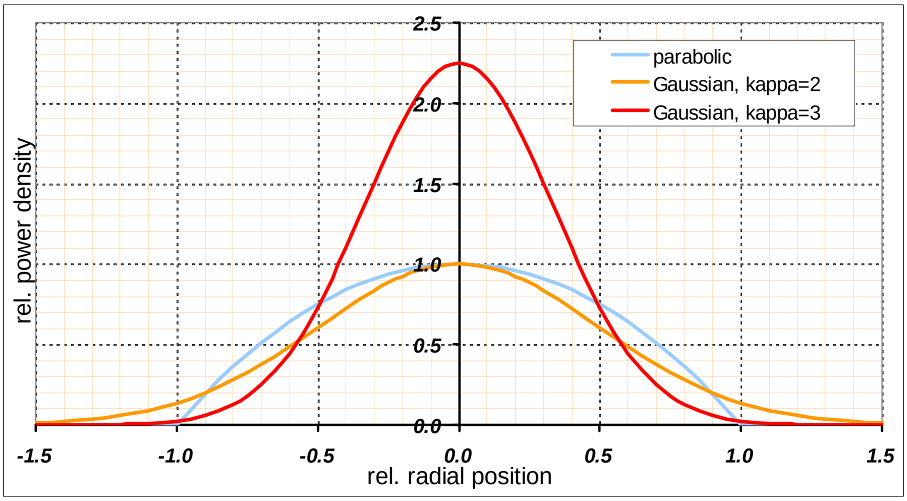

Figure 2: Heat load distribution across the beam axis.

For the presented work the following peak heat loads were assumed for tungsten:

- 3.7 kW/cm³ for 2 GeV and parabolic beam profile
- 6.6 kW/cm³ for 1.3 GeV and parabolic beam profile
- 8.3 kW/cm³ for 2 GeV and Gaussian (κ=3) beam profile
- 14.8 kW/cm³ for 1.3 GeV and Gaussian (κ=3) beam profile

4. The SNQ-type design

For this approach the SNQ design was scaled down to 1500 mm in diameter and 70 mm in active target material (tungsten) height. The temperature rise between water inlet and outlet would only be in the order of 10 K. Therefore only one pin was considered for the thermal calculation. The following conservatice assumptions were made:

- Calculation for a single pin in the position where the maximum heat deposition occurs.
- Beam profile is only considered across the beam. In beam direction the peak values are considered.
- 30 rpm synchronised to the beam pulses, so that the same pin receives a full hit each rotation.
- The mean heat transfer coefficient to cooling water is assumed with 13.000 W/(m²K)
- Above 200°C wall temperature the mean heat transfer coefficient conservatively is reduced to 900 W/m²K to account for possible local film boiling
- The positive effect of nucleate boiling is conservatively neglected
- The pin dimensions assumed for the calculation are: 18 mm OD tungsten; 19 mm OD lead (0.5 mm lead thickness); 20 mm OD zircaloy (0.5 mm zircaloy thickness); 70 mm tungsten height. 75 mm overall height.

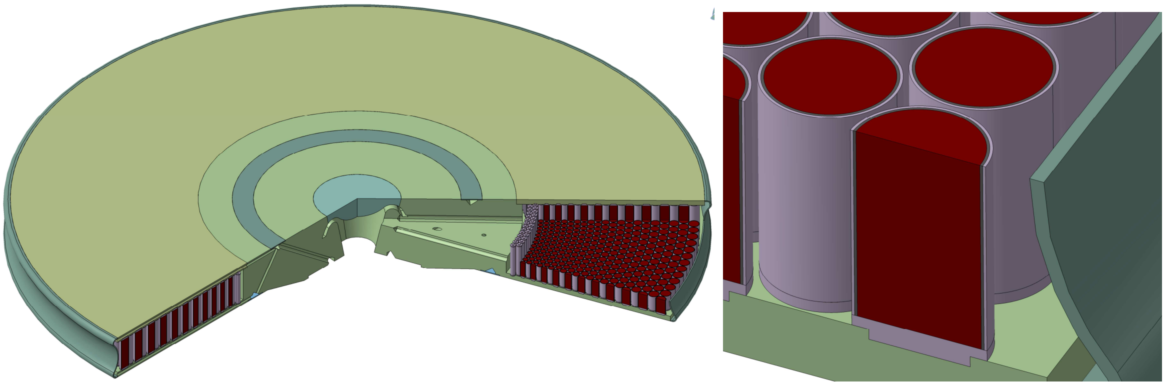

Figure 3: SNQ design scaled down to a diameter of 1500 mm.

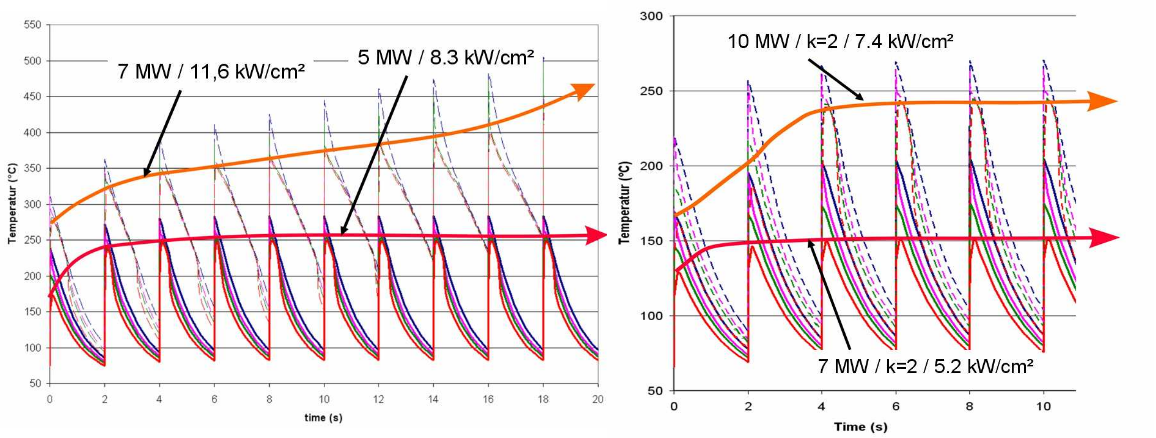

Figure 4: Heating-up for a single pin for a Gaussian beam profile (left: κ=3) and (right κ=2).

Figure 4 shows the heating curves for different peak heat loads and Gaussian profiles with κ=2 and κ=3. Even at 5 MW/2GeV and a Gaussian beam profile with κ=3, it is observed that due to the instantaneous temperature rise in the middle of the pin the surface temperature exceeds 200°C after a single pulse and therefore locally film boiling is assumed. Fortunately for this power level the regular cooling recovers during one cycle. Increasing the peak heat load even further, the film boiling area expands within the following cycles and thus the heat removal capability is more and more reduced. This effect finally leads to unacceptable high temperatures. Changing the beam profile to $\kappa = 2$ the peak heat load is considerably reduced for the same beam power. Figure 5 shows that now even 10 MW seems possible.

5. The edge cooled design

The edge cooled design consists of involute shaped tungsten blocks with flow guides on the top and bottom surface (cp. figure 5). Thus guidance of the flow is guarantied as well as flow velocity will stay constant when flowing from the hub to the outer circumference and back. Moreover the effective surface for the heat transfer is increased by the flow guides on the top and bottom surface, which will act as cooling fins.

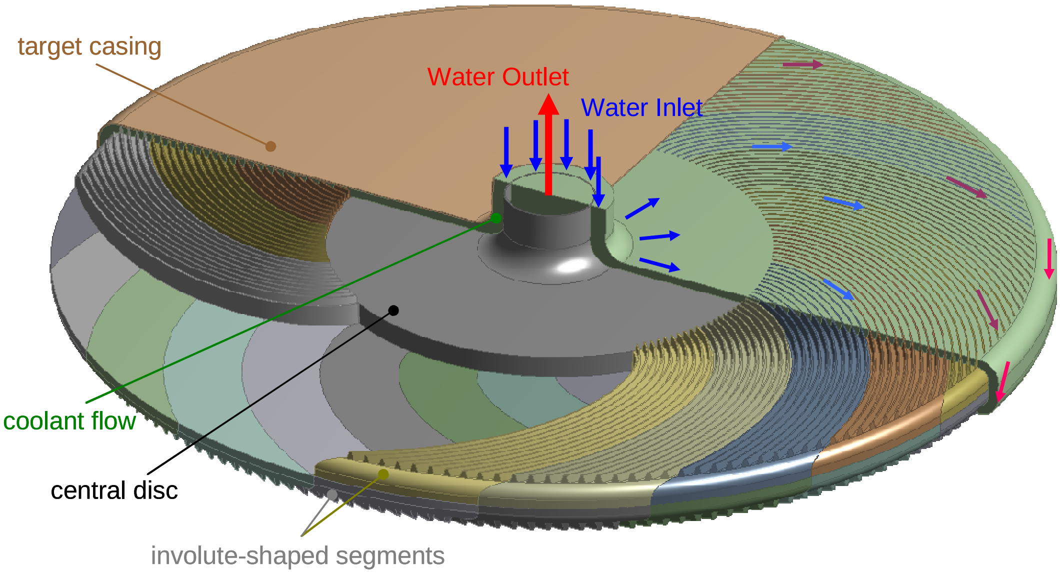

Figure 5: CFD model for the edge cooled design.

For the rotating target detailed CFD calculations were performed in order to investigate the pressure drop and temperatures for low surface temperatures (no boiling along the cooled surfaces). The first CFD calculations have already shown that for 5 MW the surface temperatures could significantly exceed the evaporating temperature of water (cp. figure 6) and therefore boiling will affect the heat transfer from the segment to the fluid. In a first approach the possible negative effect of film boiling at the front surface was considered in the CFD calculations by completely neglecting the heat transfer to the coolant flow at this surface. But these calculations could not exclude a possible burnout problem, where the surface of reduced heat transfer due to film boiling expands from pulse to pulse, till the target cooling is no longer assured.

Therefore, additional calculations were performed using a simplified thermal model of one segment without flow guides on the surface (cp. Figure 7). The results of the detailed CFD calculations were used to fit the effective heat transfer coefficients for the flow through the grooves and along the frontal part of the target for this simplified model.

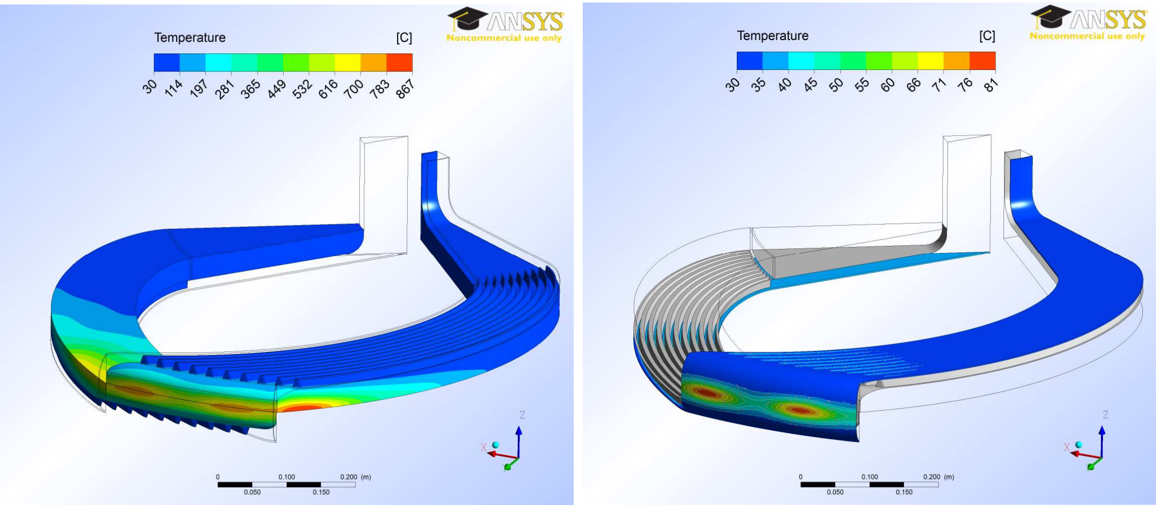

Figure 6: Segment and target container temperatures for the considered segments while passing the beam (Gaussian beam profile, κ = 3) with a rotational speed of 30 rpm.

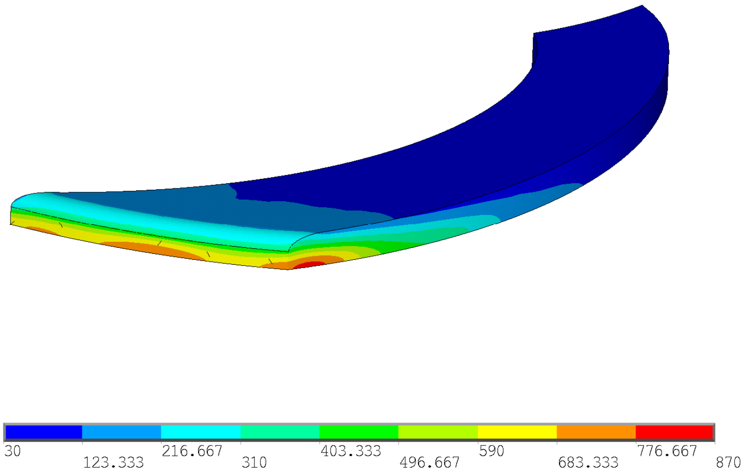

Figure 7: Segment temperatures the simplified model.

The effect of possible film boiling was now considered by significantly reducing the heat transfer coefficient, like for the calculations regarding the pin design, if the surface temperature exceeds a value of 200 °C.

The corresponding calculations have shown that 5 MW are possible if a flat power-density distribution (assumed for 2 GeV) and a parabolic beam profile or a Gaussian profile with κ = 2 are considered. For a Gaussian profile with κ = 3 the maximum segment temperatures will exceed 500 °C by far and even the time averaged maximum temperature will reach the specified design limit of 500 °C, although cooling of the target is still stable.

Further increase of the beam power will mean that at least the maximum segment temperatures will be too high, but more important is the significantly raised risk of burnout. For a flat power-density distribution (assumed for 2 GeV) and a Gaussian profile with κ = 2 the limit with respect to the beam power will be approximately 6 MW.

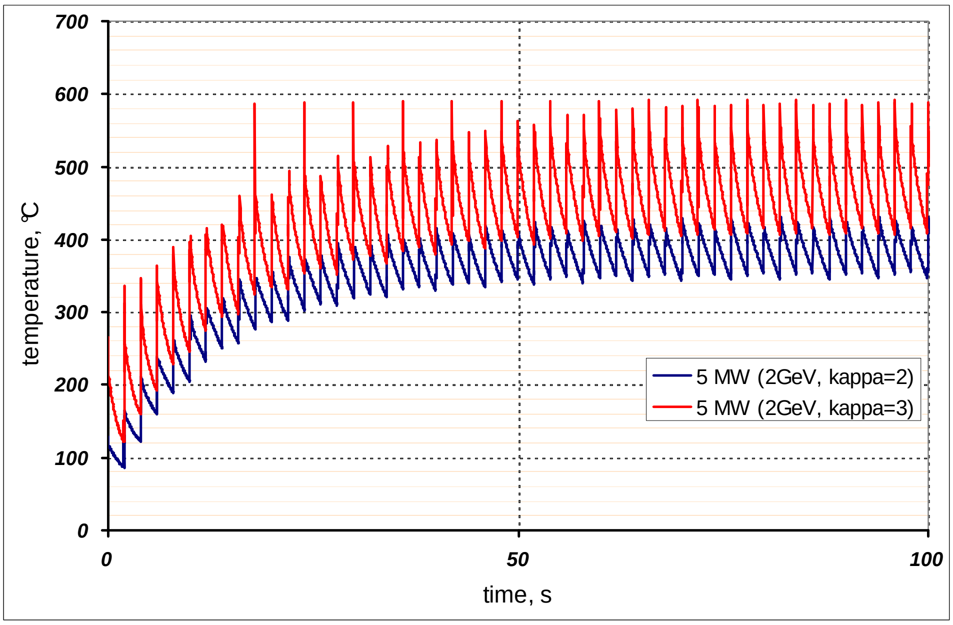

Figure 8: Segment temperatures for simplified model for 5 MW at 2 GeV and κ=2 and 3.

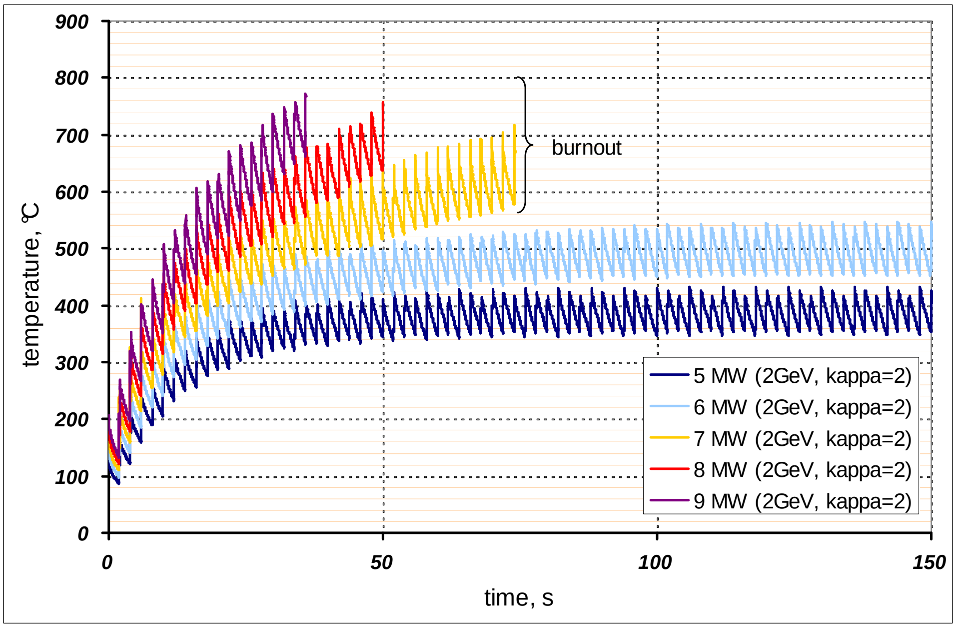

Figure 9: Segment temperatures for simplified model for 5 MW and above at 2 GeV and κ=2.

6. Conclusion and outlook

For the SNQ type (pin) design 10 MW seems not out of reach if a parabolic beam profile (or Gaussian with κ = 2) can be guarantied. This concept is basically limited by the peak energy leading to instantaneous local film boiling in the middle of the pin and significantly reduced heat transfer capabilities. The temperatures in the tungsten are well below 500°C. The penalty in neutron flux compared to pure tungsten still needs to be confirmed by MCNPX calculations

For the edge cooled design the limit is clearly the maximum temperature in tungsten (safety case temperatures <500°C) which leads to a limit of about 5-6 MW in the current configuration for $\kappa = 2$. Design optimization avoiding the boiling problems at the edge towards the front surface could probably slightly increase the power limit.

The rotating target still has a lot of potential to be optimized for even higher beam power if a compromise between both extreme design approaches shown in this paper will be considered.

7. References

1. H. Stechemesser, G. Thamm, *Target Designs for Stepwise Development of SNQ*, Proceedings of the Seventh Meeting of the International Collaboration on Advanced Neutron Sources, Chalk River Nuclear Laboratories, September 13-16, 1983, Atomic Energy of Canada Limited report number AECL-8488
2. H. Stechemesser, G. Thamm, *State of Design of the SNQ-Target*, Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, 8-12 July 1985, Appleton Laboratory report RAL-85-110
3. J. Wolters, F.Albisu, G.S. Bauer; M. Butzek; D. Filges; G. Hansen; F. Legarda; S. Martin; K. Nünighoff; M. Tello, *THERMO-MECHANICAL ASSESSMENT OF THE DISK TARGET CONCEPT FOR THE SPALLATION NEUTRON SOURCE IN THE BASQUE COUNTRY*. Eighth International Topical Meeting on Nuclear Applications and Utilization of Accelerators, July 29 – August 2, 2007 Pocatello, Idaho