TARGET–MODERATOR–REFLECTOR ASSEMBLY FOR A HIGH POWER PULSED SPALLATION NEUTRON SOURCE

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A target–moderator configuration is presented, which combines the neutronic advantages of the split target design ("flux trap" geometry) with the strongly relaxed thermohydraulic requirements of a rotating target. Moving only the most highly loaded parts, the target is composed of a twin wheel with vertical rotation axis plus a stationary part downstream of the proton beam. The twin wheel with its rotation axis parallel to the vertical proton beam essentially consists of two water–cooled disks on a common axis and separated by a gap sufficiently wide to contain an adequate number of moderators. The thickness of the two target disks is different in accordance with the optimum flux trap requirements. The annular target zone on the periphery of each disk is hit by the proton beam from the side of the thinner disk. The assembly is completed by a stationary cylindrical target separated from the second wheel by a distance appropriate for the insertion of another two to four moderators in flux trap geometry. One or two so–called back-scattering moderators can be placed in front of the first target wheel.

1. Introduction

It was realized for a long time that stationary, heterogeneously cooled solid targets for proton beam powers beyond 1 MW may either be close to their technical limits or even unfeasible at all. Therefore already the German 5.5 MW SNQ project only considered two options: a liquid metal target and as a reference design a rotating solid target [1]. Even for the 0.9 MW SINQ continuous spallation source under construction at PSI a liquid lead–bismuth eutectic was originally favoured as a target. Only because of possible radiation hazards associated with the use of liquid bismuth in strong thermal neutron fields and corrosion problems, PSI resorted to a cylindrical solid, stationary zircaloy target as the day one solution [2]. (The global concept for SINQ does not allow a solution with a moving target.) The rotating target of the former German SNQ project was planned to be hit horizontally by the protons, the in–plane depth of the target material being such as to completely stop the beam on the wheel periphery. This configuration implied a very heavy mass to be moved as well as very restricted possibilities of placing moderators next to the maximum of the fast neutron leakage. (For the German SNQ as a time–modulated source the latter argument was not stringent.)

Both the neutronically unfavourable but cheaper horizontal proton beam line and prismatic targets with wing type moderators, i.e. tangential neutron extraction, are realized in three of the existing four spallation sources. As one is interested in as many different moderators as possible with one target, the choice of three, four or even more moderators inevitably leads to only two of them placed in the maximum of the fast neutron leakage from the target. The remaining moderators will be located downstream on the tails of the leakage flux. As a remedy a vertical proton beam line enables the grouping of four equivalent wing type moderators around a vertical target. With the introduction of the split target concept [3], placing the moderators in slab orientation adjacent to the target gap, a gain in slow neutron leakage flux by a factor of approx. 1.4 was achieved compared to wing geometry.

2. The concept of a hybrid (moving + stationary) high power target

The heat deposition along the proton beam in a spallation target is very closely described by an exponential, if one neglects the build–up at the target head and the rapid decrease at the protons' range [4]. The decay constant (proton mean free path) is determined by the target material and can be estimated by an empirical expression for the absorption cross section for high energy protons [5], $\sigma_a = \pi \cdot (r_0 A^{0.33})^2$, where $r_0 = 1.26$ fm and A is the atomic mass. Values for the mean free path $\Lambda = (n \cdot \sigma_a)^{-1}$ for selected target materials are given in Table 1. So the highest thermal load is in the foremost part of any target. The maximum power density p_0 can be calculated accordingly by integrating the exponential power deposition over the proton range R, given by the empirical relationship [6] $R = 233\, \rho^{-1} Z^{0.23} (E_{gev} - 0.032)^{1.4}$ and equating the result with the total power per particle P(E) dissipated in the target. One obtains [7]

$$p_0(E) = \frac{(P(E)/\Lambda) \cdot j}{1 - \exp(-R/\Lambda)} \quad (\mathrm{MW/cm^3})$$

where P(E) is given by the empirical expression [8] $P(E) = 0.230 + 0.22\, E_{gev}$ (GeV/p) and j is the average proton current density in units of mA/cm^2. For depleted uranium the maximum power density is higher than calculated with the above formula because of fast fission (see Table 1). In the case of a 5 MW beam on Tantalum, a favourable target material, realized for instance with 800 MeV protons and a current of 6.25 mA, the maximum heat deposition is 12.5 kW/cm^3, assuming a constant current density over a beam cross section of 20 cm^2. (For comparison, this is more than 10 times the power density in the core of the High Flux Reactor in Grenoble.) In Table 1 are listed some relevant parameters for a few candidate target materials.

	Λ(cm)	R(cm)	p_0(kW/cm^3)
Pb	17.4	39.3	8.1
W	9.8	22.5	14.4
Ta	11.3	26.0	12.5
^{238}U	10.8	24.0	24.4 *)

Table 1 Proton mean free path Λ, proton range R and maximum power density p_0 for selected target materials for E_p = 800 MeV. *) Value for Uranium taken from Atchison [9].

The corresponding current density on a stationary beam window is about 300 $\mu A/cm^2$. This poses an even more serious problem on the technology of a solid target. There is still no reliable prediction possible on the window life under such conditions [10].

Clearly, the technical requirements resulting from these loads can essentially be relaxed by using a moving target. The obvious solution is a rotating solid target, as was already planned for the SNQ project. In contrast to that, the concept presented here combines the advantages of the latter with the exploitation of the split target geometry by letting the proton beam penetrate a target wheel parallel to its axis of rotation. Additionally, a substantial reduction in moving target material is achieved by partitioning the target into a rotating plus a stationary part situated downstream of the wheel. As calculations have shown [11], the optimum depth of the front part of a split target is 7 – 8 cm. On the other hand, the heat deposited in such a depth is lower by about 20 – 30 % only. Therefore it appears reasonable to consider from the very beginning two target wheels separated by the neutronically optimum distance.

The principal target–moderator–reflector assembly is shown in Figure 1, where a solution has been chosen with the proton beam from below.

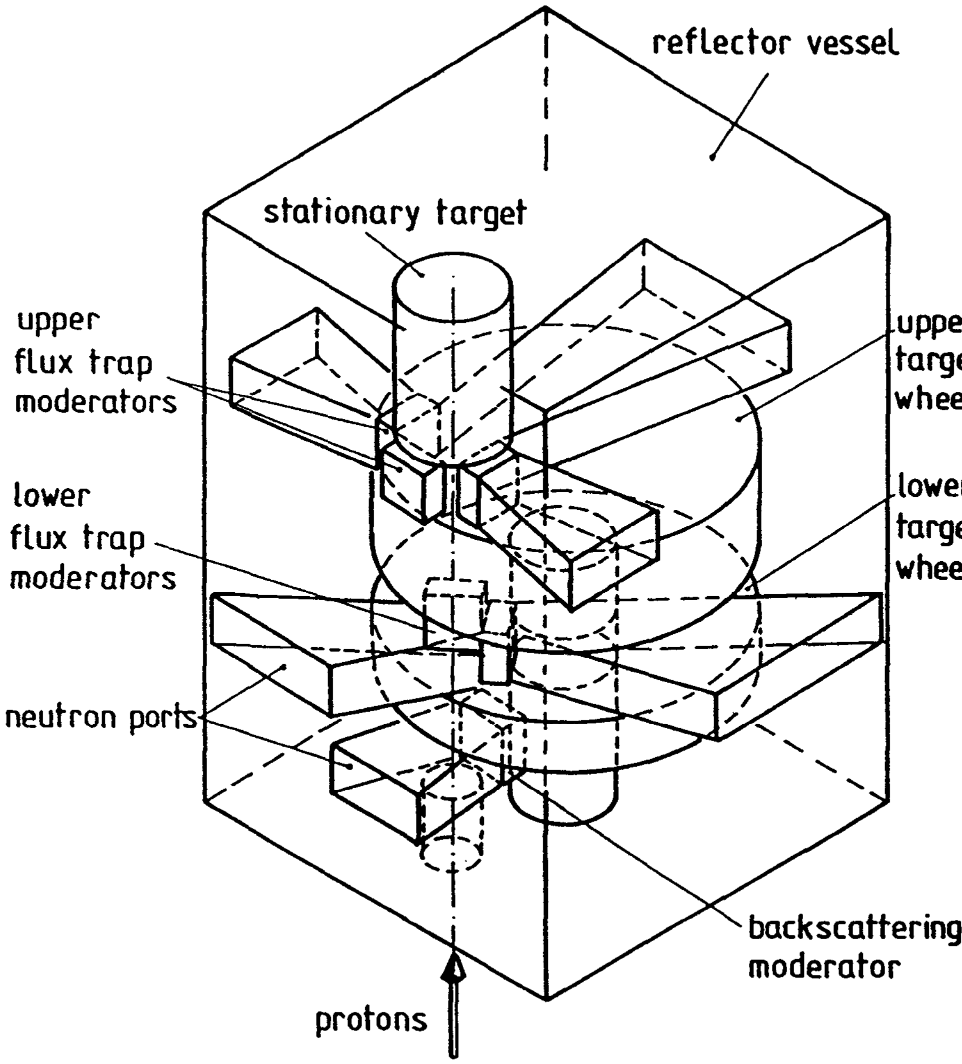

Figure 1: Sketch of the target—moderator—reflector assembly of a high power spallation neutron source. The target consists of a rotating twin wheel followed by a stationary cylindrical part. For the sake of clarity the neutron beam penetrations for one of the inter—wheel moderators are not shown.

Employing such a target assembly, the most highly loaded parts, and only these are moved. By the same token the requirements for as many different moderators as possible as well as maximum neutron beam port number can be fulfilled, i.e. flux trap configuration and vertical proton beam line are realized. The replacement of the second wheel by a corresponding stationary part in the case of medium power spallation source is a straightforward simplification of the present concept.

3. Moderator configuration

Employing a double gap target (a doubly divided, but stationary cylindrical target has been discussed recently [10]) a series of different moderator configurations and combinations can be imagined. One example is discussed in the following. A single "backscattering" moderator is placed next to the proton entrance spot of the first target wheel. Slow neutrons are extracted from the same moderator face (i.e. backscattered) as the fast neutrons are fed in. The corresponding neutron beam hole group is oriented radially away from the wheel axis.

The moderator pair in the gap between the two wheels is positioned such that it can be viewed in both backscattering and "transmission" geometry. Calculations have shown [11] that a somewhat higher flux may be obtained from the backscattering face than from the "transmission" face. So, with only two moderators four beam hole groups will be served. The two moderators are next to each other with their neutron emitting faces forming a right angle. With respect to the single backscattering moderator, however, their faces are rotated through 45 degrees, in order to obtain a symmetrical beam hole distribution. Yet, realizing a moderator pair only is not mandatory. The present concept would also admit four (or even more) "inter–wheel" moderators. But such a configuration would necessarily mean transmission geometry only. It may appear to be reasonable to decouple in that case one or several moderators of such a tight group.

The number of moderators next to the second gap, i.e. between the second target disk and the stationary target part is subject to the same considerations as just described. In the present paper a moderator triplet is assumed. Both backscattering and transmission geometry are realized and the moderator faces oriented such as to complete the 360° utilization of the target block circumference with beam holes. Schematic side and top views of the target environment are depicted in Figure 2. The top view indicates the horizontally uniform neutron beam hole configuration. Shown are the center lines of typically a beam hole triplet, each originating at one of the six moderators discussed above. A total of 24 beam holes is possible in this way.

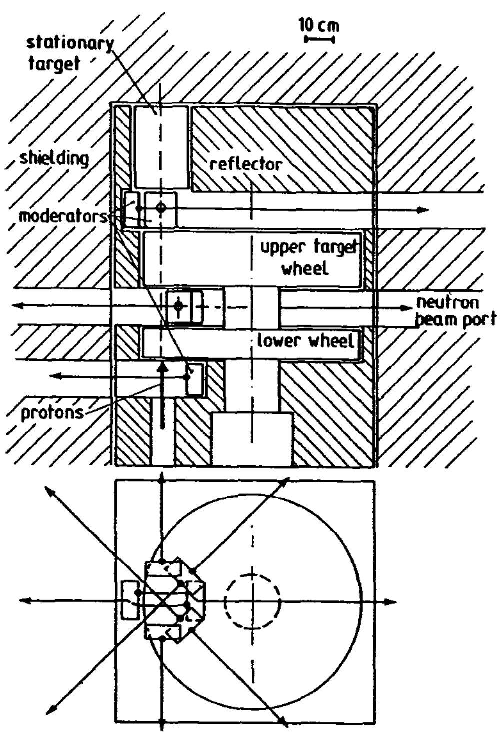

Figure 2:

Schematic side and top views of the proposed target—moderator—reflector assembly. The drawing is approximately to scale. The moderator faces viewed by neutron beam holes are marked by dots.

4. Basic technical target details

4.1 Geometric design

Target geometry and proton beam direction suggest a comparatively simple cooling scheme for the disks. The target material will be divided into flat ring–shaped plates piled on top of each other and separated by sufficiently wide gaps for coolant flow. The coolant water will be fed in through the axis, flowing outwards radially on the upper disk half and flowing back through the lower target plate gaps (see Figures 3 and 4). In this way both beam windows are cooled as well. The structural material of the wheels will be an Aluminum alloy (e.g. AlMgSi1). No engineering details such as the minimization of the number of wheel parts or welding joints will be discussed here.

In the present design the first (thin) target ring has an effective thickness of 7 cm. Including coolant gaps, beam windows and structural materials the overall wheel thickness is about 11 cm. The second (thick) target ring has an effective thickness of 12 cm and an overall wheel thickness of about 16 cm. The effective target thicknesses of the rotating disks will subject to neutronic optimizations. The figures assumed here are taken on the basis of calculations for laterally narrow targets [11]. The inherent reflector action of plate shaped targets may change these values. Both wheels have an overall diameter of 80 cm. Several criteria may be conceived for the selection of the wheel rotation frequency. As an obvious condition it will be required that two consecutive proton pulses just exclude each other spatially. Assuming a circular beam spot of 20 cm^2 as above, penetrating the wheels at a radial distance of 35 cm from the axis and taking a pulse repetition rate of 50 Hz, gives a wheel rotation frequency of about 1 Hz. The wheel drive can be achieved either hydraulically at the hub or mechanically on the circumference. A vertical cross section of the thin target wheel is shown in Figure 3.

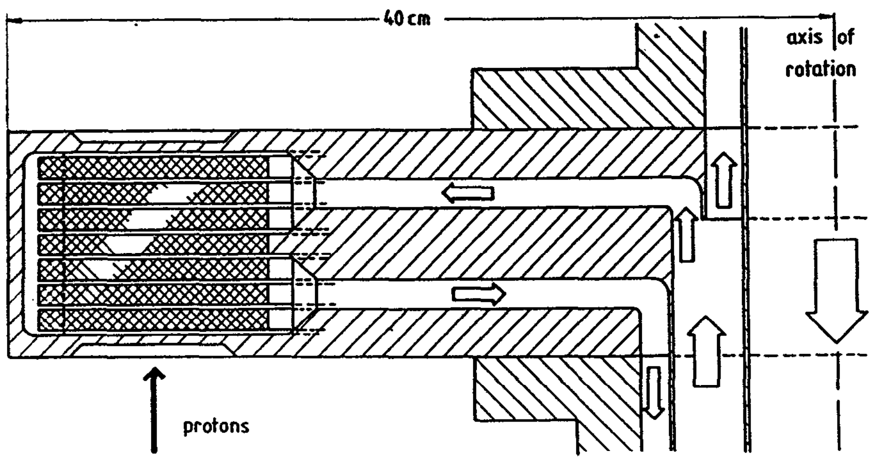

Figure 3: Vertical cut through the first (thin) target wheel (for symmetry reasons only half of the cross section is shown). The coolant flow is indicated by the open arrows.

A top view of one quadrant of a target wheel is presented in Figure 4. The stationary target will typically have an effective length of 30 cm. In order to use this target part also as a final beam stop, its length as well as the ring thicknesses have to be subject to optimizations according to the actual proton energy and target material chosen. The diameter of the stationary target cylinder will be larger than the corresponding lateral ring dimension of the rotating parts in order to intercept most of the wider forward cascade particle cone.

4.2 Thermohydraulic requirements

As the spallation reaction releases quite a number of different high energy neutral and charged particles (neutrons, mesons, protons) leaving the target, only part of the beam power, depending on proton energy, is dissipated in the target itself. At 800 MeV, for instance, this typically amounts to 50 % [8]. For the following discussion we will assume a 5 MW beam at 800 MeV and assume a total deposition of 3 MW in the target in order to obtain an upper limit for the assessment of the necessary thermohydraulic requirements. Furthermore we will take tantalum as the reference case and only consider the most highly loaded, i.e. technically most challenging first thin target wheel. Choosing water as the appropriate coolant (although cooling with Helium would circumvent the complications of radiolysis) we easily calculate the necessary volume flow for removing a total of H = 3 MW from the entire target to be

$$dV/dt = H/(c\,\rho\,\delta T) = 172\ m^3h^{-1}$$

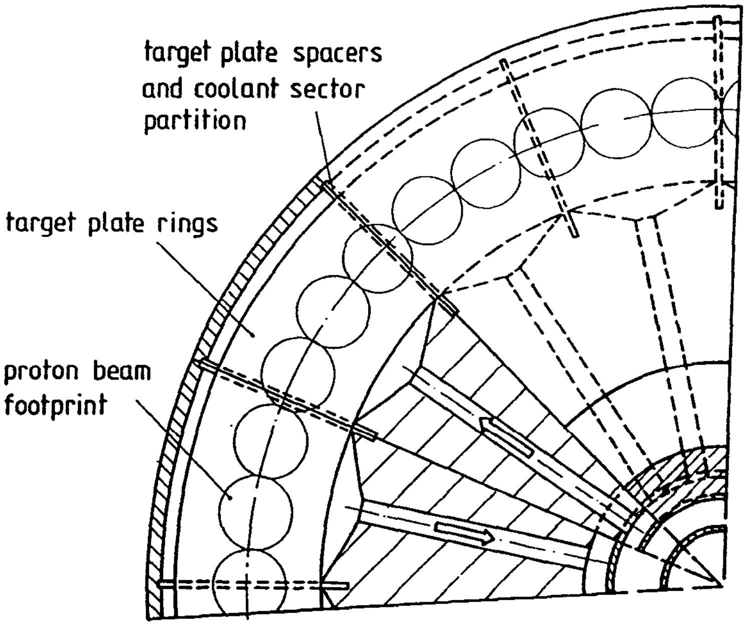

Figure 4

Three—level horizontal cut through one quadrant of the thin target wheel. Sector shown on the bottom is a cut on the level of the coolant outlet boring, adjacent sector is cut through the coolant inlet boring, top is cut halfway between the wheels. The coolant flow is partitioned into 16 independently cooled sectors.

allowing for a temperature rise of $\delta T = 15$ K. According to the exponential behaviour of the power deposition, about 1.5 MW are dissipated in the first, thin wheel, which means 85 m^3/h have to flow through this target part. For the following discussion we have chosen a partitioning of the thin target into 7 plates of equal thickness of 1 cm separated by coolant gaps of $d = 0.2$ cm. With a total cross sectional area $A_{tot} = 0.015\ m^2$ the average flow velocity through the target gaps is

$$<v> = (dV/dt)/A_{tot} = 1.7\ ms^{-1}.$$

The Reynold's number for flow in a channel of narrow rectangular cross section is given by $Re = 2d<v>/\nu$ (the kinematic viscosity ν taken at $T = 50^0C$, $\nu_{50} = 0.56\cdot 10^{-6}\ m^2s^{-1}$), i.e. $Re \simeq 12100$. This number means turbulent flow, the corresponding pressure drop in one target coolant channel being therefore [12], $\Delta p_t = \ell\zeta\rho<v>^2/(2d_h) \simeq 1090\ Nm^{-2}$, where ℓ is the channel length, $\zeta = 0.316\cdot Re^{-0.25}$, ρ is the water density and $d_h = 2d$ the hydraulic channel diameter. The pressure drop in a radial feed pipe (see Figures 4 and 5) is $\Delta p_f \simeq 1240\ Nm^{-2}$, i.e. of the same order of magnitude. According to the cooling scheme (compare Fig. 4) the flow resistances in each sector are in series. We therefore obtain a pressure drop in the straight parts $\Delta p_s = 2\ (\Delta p_t + \Delta p_p) = 4660\ N/m^2$, which is a small value. Major contributions to the total pressure drop result from both the flow turns with low bending radii at the wheel axis and at the rear plate edges. These can be estimated by $\Delta p_{turn} = d_h\rho<v>^2/r$, where r is the radius of curvature. With $d_h \simeq r$ we obtain $\Delta p_{turn} = 2890\ N/m^2$. As there are 8 turns, the total loss is $\simeq 23000\ N/m^2$. Adding to this the above value for Δp_s we have as an order of magnitude estimate $\Delta p_{tot} \simeq 28000\ N/m^2$, corresponding to

$$\Delta p_{tot} \simeq 0.28\ \text{bar}.$$

Let us now turn to the temperatures and their variations we have to expect in the course of the pulsed proton operation. Let us assume as before a pulse repetition rate of $f_{rep} = 50\ s^{-1}$. The pulse duration t_p will be of the order of a few microseconds only, so we can regard the power deposition as instantaneous. At first we are interested in the corresponding sudden temperature increase of the most highly loaded target part during a single proton pulse. This is given by

$$\Delta T = p_0/(c\ \rho\ f_{rep}), \qquad (1)$$

where p_0 is the time average maximum power density, c is the specific heat capacity and ρ the density of the target material. For tantalum, p_0 is 12.5 kW/cm³ (Table 1), and we obtain for the first few target plates a temperature rise of $\Delta T^{ta} = 96$ K.

As the target rotation frequency is $f_{rot} \simeq 1\ s^{-1}$, the heated volume will cool down by a certain amount during 1 second. Consecutive proton bursts will then result in a sawtooth like behaviour with a rising characteristic until an "equilibrium" temperature is reached, on which oscillations of the above amplitude are superimposed. In order to obtain a quantitative picture of the temperature course after start–up and the time elapsed to reach stationary conditions we calculate the transient heat conduction for plate geometry according to the heat diffusion equation $\partial^2T(x,t)/\partial x^2=(\rho c/\lambda)\partial T(x,t)/\partial t$. The exact solution of this equation is given by the infinite series [13]

$$T(t,x) = T_w + [T(0,x) - T_w]\sum C_i\cdot \exp[-\zeta_i^2 Fo(t)]\cdot \cos(2\zeta_i x/D)$$

where x is the distance from plate center to surface and T_w is the coolant temperature. Fo(t) is the Fourier number, a dimensionless quantity defined as $Fo = (4\lambda/\rho c D^2)t$ (thermal conductivity λ, plate thickness D, time t). C_i and ζ_i are tabulated quantities [13] depending on another dimensionless number, the Biot number $Bi = \alpha D/2\lambda$, where α is the heat transfer coefficient. Only the first term in the above series needs to be retained if $Fo > 0.2$. For tantalum, $Fo = 0.874\ t$, i.e. for $t > 0.23$ s and identifying $T(0,x) - T_w$ with ΔT from equation (1) we obtain the approximate solution

$$T(t,x) = T_w + \Delta T\cdot C_1\cdot \exp[-\zeta_1^2 Fo(t)]\cdot \cos(2\zeta_1 x/D),$$

a single exponential decay till the next proton burst at $t = t_{rot}$. (For very short times, in fact, more terms of the exact solution were adequate, resulting in slightly blunter sawteeth tips, but not changing the long time features.) With $\alpha = 1.0$ W/cm²K (see below) and 1 cm thick plates we have $Bi = 0.92$, which gives $C_1 = 1.112$ and $\zeta_1 = 0.834$. With $q \equiv C_1\cdot \exp[-\zeta_1^2 Fo(t_{rot})] = 0.653$, the center temperature $(x = 0)$ of a target volume element immediately after it has been hit by the n–th proton pulse is given by

$$T_i^{(n)} = T_w + \Delta T\cdot (1 + q + q^2 + \ldots + q^{n-1})$$

and at the end of the following wheel revolution the temperature in the center plane of that volume element is

$$T_f^{(n)} = T_w + \Delta T\cdot q\cdot (1 + q + q^2 + \ldots + q^{n-1})$$

The maximum and minimum temperatures in the stationary case $(n \to \infty)$ are then given by

$$T_{cmax} = T_w + \Delta T/(1 - q) = 327^oC \tag{2}$$

and $T_{cmin} = T_w + q\cdot \Delta T/(1 - q) = 231^oC$ respectively. The "equilibrium" temperature in the center of the first plate is therefore $T_c^{equ} = (T_{cmax}+ T_{cmin})/2 = 279^oC$. In the same manner we calculate the surface temperature $(x = D/2)$. We now define $q' \equiv C_1\cdot \exp[-\zeta_1^2 Fo(t_{rot})]\cdot \cos(\zeta_1)$. For tantalum $q' = 0.438$ and we obtain

$$T_{smax} = T_w + \Delta T/(1 - q') = 221^oC. \tag{3}$$

Correspondingly $T_{smin} = T_w + q'\cdot \Delta T/(1 - q') = 125^oC$ and $T_s^{equ} = (T_s^{max}+T_s^{min})/2 = 173^oC$. In Table 2 are given some relevant thermodynamic parameters and the operating temperatures for selected target materials and for aluminum as a window material.

	$\overline{p_o}$(W/cm³)	c·ρ(Ws/cm³K)	λ(W/cm K)	T_c(°C)	T_s(°C)	$\Delta\hat{T}$(°C)
Pb	186	1.46	0.346	286	209	110
W	331	2.59	1.674	305	267	111
Ta	288	2.50	0.544	327	221	96
^{238}U	561	2.24	0.251	912	388	218
Al	83	2.42	2.110	(114)*	107	30

Table 2 Thermodynamic parameters and operating temperatures for selected target materials and for aluminum as window material. The items are: specific heat c, density ρ, thermal conductivity λ (at 20°C), maximum plate center temperature T_C (equ. 2), maximum plate surface temperature T_S (equ. 3), (T_C and T_S are for $T_W = 50$°C) and temperature jump ΔT (equ. 1) during a single proton pulse. p_0 is the revolution average power density. Thickness of a single target plate is 1 cm in each case. Aluminum window thickness is 0.5 cm. *) Estimated temperature at the vacuum side.

The temperatures in Table 2 have been calculated assuming equal target geometry and coolant flow (1 cm thick target plates separated by 0.2 cm wide coolant gaps). The temperature course after start–up is shown in Figure 5 for the center plane of the first plate. (Note that the temperature above coolant is plotted.) As can be seen, equilibrium is reached after about 15 wheel revolutions corresponding to about 13 seconds.

The result for the "equilibrium" target temperature can be checked by the following simple consideration. The revolution–average maximum power density $<p_0>$ in the rotating target is given by $<p_0> = (f_{rot}/f_{rep})\cdot p_0$. For tantalum $<p_0>^{ta} = 0.288$ kW/cm³. This means that we have to transport $q_o = 144$ W/cm² through each of the two water

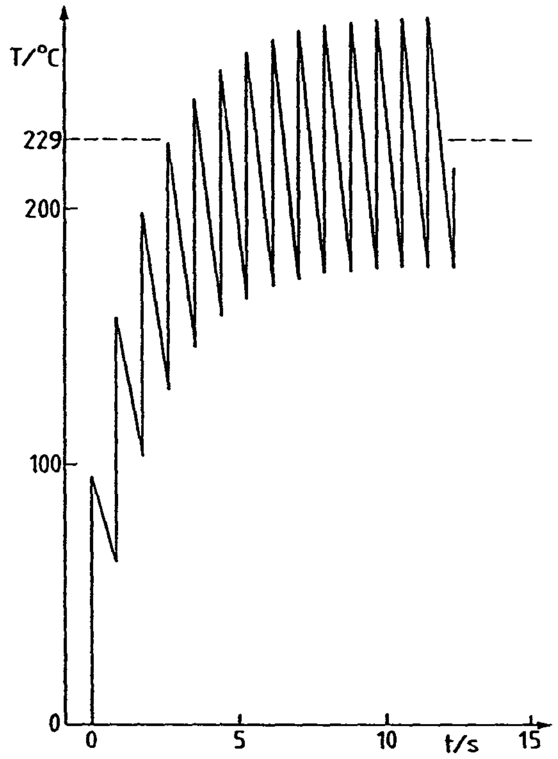

Figure 5

Temperature course in the center plane of the first plate of a Tantalum target after start–up of the proton beam. Note: Plotted temperature is above coolant.

cooled surfaces of the plates. In order to calculate the target surface temperature, we need to know the heat transfer coefficient α of a narrow coolant gap, which is given by $\alpha = \lambda \cdot Nu/d_h$. The Nusselt number for turbulent flow is given by the relation [12] $Nu = 0.037(Re^{0.75}-180)Pr^{0.42}$. With $Re \simeq 12100$ from above and the Prandtl number $Pr = \nu\rho c/\lambda = 3.61$ we obtain $Nu \simeq 61.8$. With $\lambda = 6.48 \times 10^{-3}$ W cm^{-1}K^{-1} for water at $T_w = 50^oC$ and $d_h = 2d$ ($d = 0.2$ cm) we finally have $\alpha = 1.0$ Wcm^{-2}K^{-1}. The average target surface temperature T_s is then given by $T_s = T_w + q_0/\alpha A = 50^oC + 144^oC = = 194^oC$. The temperature in the target plate center is given by $T_c = T_s + \langle p_0 \rangle D^2/8\lambda$ [12] (λ is the heat conductivity of the target material and D the plate thickness). For tantalum plates with D = 1 cm we obtain $\langle p_0 \rangle D^2/8\lambda = 66^oC$ and $T_c^{ta} = 260^oC$. Within the approximations made this is close to the corresponding temperature $T_c^{equ}=279^oC$ from above. For comparison, in a non–moving Ta–target of the same geometry the maximum temperature were $T_{max} \simeq 3190^oC$, which is above the melting temperature.

4.3 Proton beam window

Like the target plates the proton beam windows are subject to similar considerations with respect to their cooling requirements. The maximum power density in an Aluminum window ($R = 108$ cm for 800 MeV, $\Lambda = 37$ cm) is $p_0 = 3.6$ kW/cm^3, yielding a temperature jump of 30^oC during a proton pulse. The time average power density is $\langle p_0 \rangle = 0.083$ kW/cm^3. The power deposited in the 5 mm thick window has now to be removed through one surface only (we neglect radiation cooling on the vacuum side), i.e. we have to transport 41.5 W across each square centimeter to the coolant. The corresponding window temperature is about 107^oC on its water cooled face and assumes estimated 114^oC on the vacuum side. Therefore, temperature is not of particular concern in stress analysis and mechanical design of the beam windows.

5. Concluding remarks

The target concept presented in this paper appears to have a series of advantages as compared to stationary or alternative rotating target designs, i.e.

- flux trap geometry and vertical proton beam line with a rotating disk–shaped target
- specific heat deposition in the target material lower by a factor of about 40
- lower specific radiation damage in the target material
- proton current density on the beam window less than 10 μA/cm^2
- optimum decoupling of the different moderators (no cross talk through target disks)
- inherent reflector action of the laterally extended target disks
- larger proton beam cross section possible, e.g. elongated tangentially to the disk circumference
- only part of the necessary target volume has to be moved
- wheel hub not in the immediate neighborhood of the forward directed high energetic cascade particles (less demanding wheel bearing and coolant inlet conditions)

Clearly, the presented target–moderator concept also holds for a proton beam from above, if the sequence of target parts is reversed as well. In that case the last of the just mentioned advantages is no longer valid.

Some final remarks on user requirements seem to be suitable here. It is generally accepted today [14] that a new spallation source should basically provide four types of moderators, which are characterized according to their spectra and pulse shapes. The present target concept quite naturally accomodates three spatially separated moderator groups. In the example discussed above, even six single moderator locations have been identified. Therefore, a basic set of four differently performing moderators can easliy be realized. According to the user requirements, this set is composed of two pairs of moderators, one pair at ambient and the other one at low (possibly liquid hydrogen) temperature, respectively. At each temperature there has to be both a high intensity (coupled, unpoisoned) and a high resolution (decoupled and/or poisoned) moderator. Detailed numerical calculations still to come have to guide the assignment of these moderators to their respective locations in the target environment.

A tentative allocation is the following. The high intensity thermal moderator will be the backscattering moderator before the first wheel. The pair of inter–wheel moderators will serve as both the high intensity and high resolution cold moderators. The high resolution moderator may be heterogeneously poisoned and deliver different pulse shapes from its two faces. The triplet on top may either consist of both high intensity and high resolution thermal moderators or a combination of thermal and cold ones, if they are adequately decoupled.

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