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Overview on spallation target design concepts and related materials issues

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A B S T R A C T

From a modest beginning of a few kW of beam power spallation sources have now evolved into systems that must be able to handle several MW, mostly delivered in short pulses of less than microsecond duration. The high radiation field and high instantaneous heat deposition which spallation targets, in particular for the new high power sources, are subject to have led to several different design concepts which aim at circumventing or reducing the deleterious effects on the materials in the targets. Efficient cooling and high neutron source density are competing requirements which can be best reconciled by moving the target material out of the reaction zone and removing the heat elsewhere before returning the material back into the proton beam. One option is the use of a flowing liquid metal, which has been the method of choice in most of the recent spallation source designs, but requires solutions to a variety of new problems, such as liquid metal corrosion, cavitation erosion and e.g. in the case of PbBi, or Pb, high temperature gradients. Using a rotating solid target is an option in certain cases but still has to cope with the instantaneous load levels. While it may help to keep the average heat load and radiation damage in the target material low and thus extend the target life time by more than an order of magnitude, it still has its own design and materials issues. Opportunities to carry out research in this field are rather limited because the effects can hardly be simulated off line and, apart from spallation targets in operation, almost no facilities are available.

1. Introduction

Although there is only a relatively small number of spallation neutron sources currently in operation world wide, substantial efforts are being made to develop target systems that can serve in a new generation of facilities whose proton beam power is of several megawatts. Since about 50% of the beam energy is deposited in the target in a relatively small volume, heat removal is a major concern. On the other hand, a large volume fraction of coolant (usually H_2O or D_2O) dilutes the target material and hence the source brightness. The use of the more or less straight forward plate or block technology applied in early designs (KENS, IPNS, WNR, ISIS) is therefore limited to low and medium power installations. SINQ, which became operational in 1997 at a beam power level of 600 kW is using a target of lead rods clad in steel or, more recently, in Zircaloy. This facilitates heat removal and, even more important, reduces the thermal stress in the target considerably. Facilities aiming at even higher beam power (ESS, SNS, JSNS) have opted to use a flowing liquid metal (mercury), among others because this allows to move the heated target material away from the beam interaction zone and cool it elsewhere. This concept still leaves a stationary window of the target container in the beam, which now becomes the life time limiting component. A long service life of the target is, however, highly desirable both for reasons of cost and source availability. Down times necessary to change a target or its container will normally be of the order of a week. In an attempt to avoid this problem a windowless liquid metal target has been proposed for the Canadian ING-concept (60 MW_b) in the early 1960ies and was studied as a backup option for the German SNQ project in the early 1980ies. This concept is now under development again for the MYRRHA-project in Belgium, which aims at a proton beam driven fast neutron irradiation facility. An alternative solution to avoid excessive radiation damage on the target container is the concept of a rotating target, which was first studied for the German SNQ project in the early 1980ies and is now being considered for the 2nd target station of SNS and for the Chinese CSNS project.

The present paper reviews these different design options and points out associated materials issues and development needs with a view on high power facilities.

2. Target materials

In spallation neutron sources, in particular for pulsed operation, it is desirable to have a bright source of primary neutrons for optimum coupling into the – usually small – moderators. In order to retain a narrow pulse of moderated neutrons, it is necessary to slow them down quickly and without allowing them to spread over

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Table 1
Overview of target concepts in different spallation neutron sources. In most cases different target materials have been used or followed up in the design. Early ones are given in parentheses. W–Ta stands for tantalum clad tungsten.

Period	Project country	Beam power	Target concept	Status (2008)
1960ies	ING Canada	60 MW	Flowing PbBi, windowless	Cancelled
Late 1970ies	KENS Japan	3 kW	Solid (U,Ta),	EoL 2005
	IPNS USA	7 kW	W–Ta solid U	EoL 2008
	WNR USA	70 kW	Solid W	Operating
Early 1980ies	ISIS UK	160 kW	Solid (U) (Ta) W–Ta	Operating
	SNQ Germany	5.5 MW	Solid Pb (U), rotat. Flowing PbBi, windowless (opt.)	Cancelled
1997–2007	SINQ CH	600 kW	Solid Pb	Operating finished
	MEGAPIE		liquid PbBi	
Early 2000s	ESS Europe	5 MW	Flowing Hg with stationary window	Deferred ramping up commiss
	SNS USA	1.4 MW		
	JSNS Japan	1 MW		

a large volume. This is why small moderators of high scattering length density are desirable and a bright primary source is important. In principle all high density heavy materials make suitable spallation targets because the spallation reaction takes place in all elements, albeit with an increasing number of neutrons released as the atomic number of the element increases – and hence the number of neutrons present in the nucleus. In practice, however, there are a number of requirements, which limit the choices considerably. The most important ones for solid targets are:

- good thermal conductivity at the temperature of operation;
- small thermal expansion coefficient to minimize thermal stress (in particular fatigue stress);
- good elastic properties and sufficient ductility even after irradiation;
- moderate activation and afterheat production for ease of emergency and shutdown cooling;
- resistance to corrosion even under irradiation and
- reasonably good manufacturability and joinability to other materials (by welding, hipping or other techniques).

Given its physical and metallurgical properties, tantalum would be the most suitable material for solid spallation targets. It has a very high melting point, is relatively easy to machine and weld, is very resistant to corrosion and shows good neutron yield. It was also found to retain excellent ductility even after irradiation to as much as 13 dpa in the ISIS target [1,2][1]. Its disadvantage is its relatively high neutron absorption cross section, also in the epithermal energy range. This leads to high radioactivity and afterheat of used targets. Calculations for the case of ESS (5 MW_b) showed that, after one year of irradiation Ta has about an order of magnitude higher afterheat than W or Hg [3]. It is mainly for this reason that the two facilities which used Ta in the past (KENS and ISIS, cf. Table 1), have decided to switch to W targets clad with Ta.

Its density of 19.3 g/cm^3 (vs. 16.6 for Ta) and about 2.5 times better thermal conductivity (140 vs. 60 W/(m K) at 100–200 °C), make tungsten a very desirable spallation target material. However, it was found to corrode with water under irradiation [4,5] which is why Ta-cladding is used. Furthermore, it is brittle at room temperature, with its brittle-to-ductile transition temperature increasing from about 600 K in the unirradiated state by as much as 29 K/(10^{19} n/cm^2). So, while Ta-clad W-plates may be a viable solution at low and medium beam power, it would be highly desirable to find a more ductile alloy for higher power applications. W–Re alloys might be good candidates but are not yet well researched, in particular under irradiation. Furthermore, the use of 0.5 mm thick Ta-cladding for corrosion protection is not optimal because of the different thermal expansion of Ta and W. Also, it adds to the overall radioactivity the more, the thinner the target plates must be for cooling reasons. Developing a better corrosion protection for W which does not penalize neutron yield would be highly desirable.

Another candidate target material which should be mentioned in this context is depleted uranium. It has about 1.8 times higher neutron yield than Ta or W, albeit at the expense of a roughly two times higher heat release. Unfortunately experience with uranium plate targets is very poor: In IPNS as well as in ISIS they failed after less than 250 mAh of beam loading [6]. The reason is not clear, but it might be due to recrystallization effects under thermal cycling. In any case, it would be highly desirable to develop a uranium alloy which does not suffer from this effect and which could be used for optimum neutron production efficiency. In particular if rotating targets become available, the use of a suitable uranium alloy might be an option because, just like heat deposition and radiation effects, also delayed neutron emission is distributed over a large target mass, only a fraction of which is close to the moderators. In stationary uranium targets emission of neutrons between pulses from delayed neutron precursors was found to require special attention.

As for liquid metal targets the requirement of a reasonably low melting point limits the choice to essentially mercury ($T_m = -38.9$ °C) and the eutectic mixture of 45% lead and 55% bismuth (LBE, $T_m = 125$ °C) and potentially lead ($T_m = 327.5$ °C). Mercury, which has a relatively high thermal neutron absorption coefficient preferably, lends itself to the use in short pulse sources, whereas LBE is the preferred material for liquid metal targets in continuous and possibly also long pulse sources. A problem with LBE is the formation of α-active ^{210}Po and the need for control of the oxygen level to prevent wall corrosion, as discussed below.

3. Plate targets for high beam power

Targets made up from plates cooled by water flowing across their surface have been the concept of choice since the early spallation neutron sources (IPNS, ISIS) came along. Their design is relatively straight forward if lateral heat transport in the plate is neglected. The thickness of the target plates will be graded to account for the decreasing heat release as the proton beam is attenuated along its passage through the target. Extensive studies have been carried out by Takenaka and coworkers [7]. For the case of a beam power of 600 kW and a target made from all W-plates the thinnest plates must be no more than 7 mm thick in order to limit

[1] Byun and Maloy [45] found no ductility left in Ta after reactor irradiation to doses even as low as 0.14 dpa but, according to one of the authors, this might be due to oxygen pickup during baking of the samples in an insufficiently good vacuum prior to irradiation.

the surface heat flux to less than 300 W/cm^2. This value the authors consider the allowable limit for a flow velocity of 10 m/s in the 1.5 mm wide channels between the plates. This results in an 18% dilution of the target material. As mentioned above, the situation will be even worse if Ta-cladding must be used to avoid corrosion of the W, because of the higher heat production and poorer heat conduction of Ta. For high power his means that realistically the design will have to be more conservative in order to account for the pulsed nature of the beam (instantaneous heat flux) and for potential degradation of the thermal conductivity under irradiation.

As an extreme example we quote preliminary studies carried out for a plate target for the 5 MW beam of the ESS project as a potential alternative to the liquid mercury target [8,9]. A sketch of the pre-conceptual design is shown in Fig 1. The plates were assumed to be bent in vertical direction to avoid uncontrolled buckling under their thermal stress during operation. Due to the curvature of the plates the cooling channels are of variable width with a minimum of 0.7 mm at the top and bottom ends.

In view of uncertainties in the manufacturing process of thin Ta-clad W-plates and also because the Ta fraction would be high anyhow, it was assumed that the target material was all Ta, (with an option of switching to clad W-plates at least for the thicker plates in the downstream region of the beam). For this case the (time average) heat flux in the plate center and the plate thickness are shown in Fig. 2.

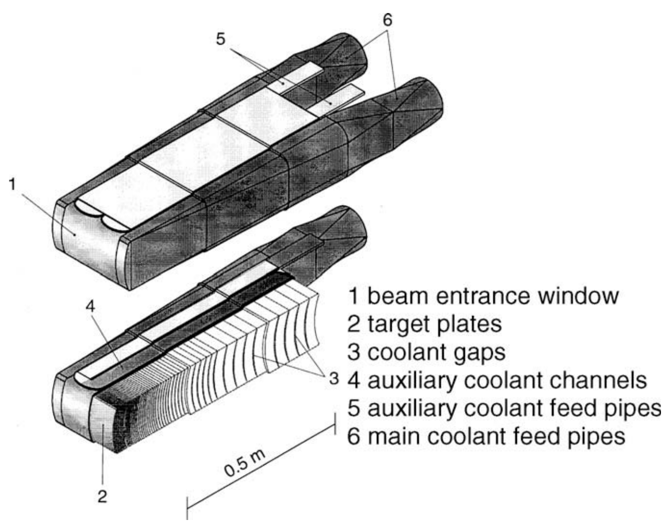

Fig. 1. Sketch of the pre-conceptual design of a plate target for the 5 MW beam of ESS.

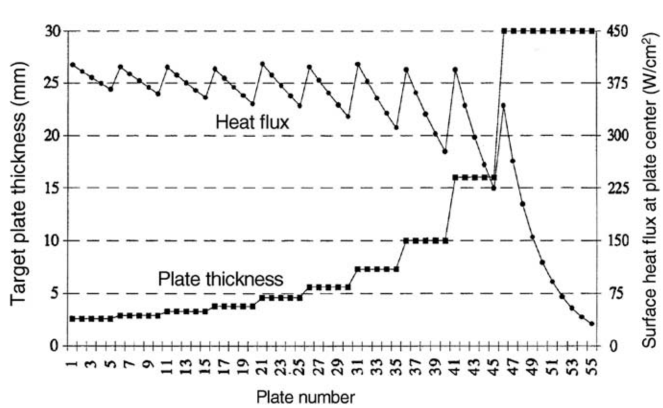

Fig. 2. Time average heat flux in the plate center and plate thickness as a function of plate number for Ta target studied for the 5 MW$_b$ ESS project.

Table 2
Thermal hydraulics parameters of the Ta-plate target studied for ESS at 5 MW$_b$.

Peak heat deposition (time average)	3.1 kW/cm^3
Maximum surface heat flux (time average)	375 W/cm^2
Heat transfer coefficient	3.5 W/cm^2 K
Max plate surface temperature	180 °C
Max plate mid-plane temperature	250 °C
Water velocity in gaps	7.5 m/s
Pressure drop across gaps	0.1 MPa
Minimum plate thickness	2.5 mm
Volumetric coolant flow	80 kg/s

A summary of various thermal hydraulics parameters of the concept is given in Table 2.

Again, these calculations were carried out using the thermal conductivity of unirradiated Ta. It should also be noted that the surface heat flux of up to 380 W/cm^2 at 7.5 m/s flow velocity is more optimistic than the one used by Takenaka et al. (300 W/cm^2 at 10 m/s). Although estimates of the shock wave effects in the plates [8] did not produce prohibitive results, if a target so close to its feasibility limit were to be built, more data on radiation effects on properties such as thermal conductivity and fatigue limit would clearly be needed.

The optimistic estimate for the service life of this target was ca. 45 days and it was clear that afterheat removal had to be maintained during target change-out in order to achieve any kind of acceptable source availability. Work on the concept was finally stopped in favor of the mercury target chosen as the reference concept for ESS.

4. Rod targets

A rod target, i.e. a target made up from cylindrical target elements and cooled by water in cross-flow was first examined in the frame of the German SNQ project [10,11]. While some of this work was reported at the ICANS-meetings VI–VII ([12–16], much of it was summarized in a report at the end of the project definition phase (Phase B) in 1984 [17]. Target materials to be used in the different development stages of the facility (from 1.75 MW$_b$ at 350 MeV to 5.5 MW$_b$ at 1100 MeV, long and short pulsed) were lead, tungsten and depleted uranium. In all cases an aluminum alloy was going to be used as canning material. Much effort went into characterizing materials under the anticipated operating conditions and into thermo-mechanical studies of the target pins. In order to allow reasonable heat removal parameters the pins were to be arranged in the outer zone of a 2.5 m diameter rotating target wheel, which would allow to achieve a roughly 200-fold dilution of the radiation and heat load relative to a stationary target. In this way, it was possible to work with pins of 20 mm diameter and thus minimize the average density reduction by the cooling water between the pins. Average operating temperatures at 5.5 MW$_b$ were calculated as 100 °C for W and 250 °C for U with a temperature jump of 50 respectively. 100 °C during the beam pulse once every target revolution (2 sec). Development work was terminated when the project was cancelled in the spring of 1985.

The concept of a pin target was picked up again during the Swiss SINQ project, initially as a backup solution to a liquid metal target and later on as the start-up target for the facility. Since SINQ has vertical beam injection from underneath, the pins are arranged horizontally and are cooled by D_2O in a cross-flow configuration with the water flowing upwards between the horizontal rods. The cage holding the pins is enclosed in a double-walled and separately cooled container of AlMg3.

Again, most of the engineering development work was documented in internal or in conference reports, e.g. [18–20], and an overview has been published [21].

The first two SINQ targets designed for start-up and early development work consisted of arrays of 10 mm diameter Zircaloy rods mounted in a cage in hexagonal close packing arrangement with a pitch of 12.8 mm. From the 3rd target, Mark-III (Fig. 3), on lead-filled steel tubes were used, prototypes of which had been tested in target Mark-II. This yielded 50% more neutron flux in the reflector, but – because of its novelty-required careful theoretical assessment [19,20] in order to obtain an operating license. Since SINQ is a continuous neutron source, lead is the target material of choice because of its good neutron yield and low thermal neutron absorption coefficient. Due to its softness and corrosion with water however, it cannot be used without canning. Three different canning materials were contemplated: AlMgSi, Zircaloy and stainless steel. It was found that leaving a small gap in the top of the (horizontally mounted) rod allows the lead to deform plastically and results in only half of the stress in the canning tube during operation that would be obtained in a completely filled tube. The calculations showed that, as expected, the temperature in Zircaloy and steel canned pins is higher than with AlMgSi canning, but this is not an undesirable feature because the lead softens more and fills the expansion gap during operation. Due to some uncertainties regarding hydrogen embrittlement of the Zircaloy from pickup of hydrogen produced in the lead, the decision was made in favor of stainless steel canning for Target Mark-III. Again, Zircaloy canned rods have been tested in the mean time and the next target will, among other improvements, be made of Zircaloy canned lead and is expected to yield a further increase in neutron flux in the reflector [22].

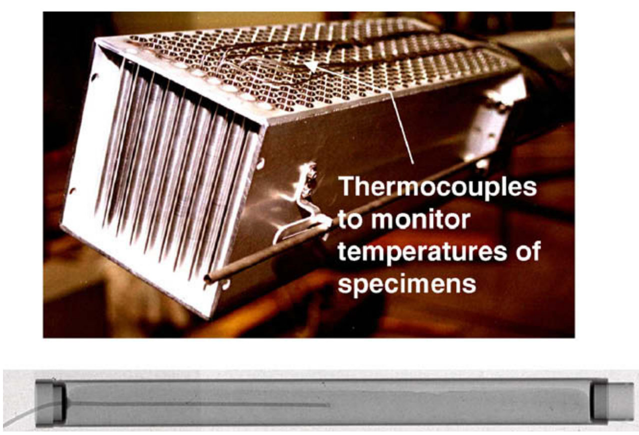

Fig. 3. Top: the SINQ-rod target Mark-III. The target rods are of 10 mm diameter in a hexagonal arrangement with a pitch of 12.8 mm. The first rows are empty aluminum tubes for coolant flow rectification. Bottom: neutron radiograph of a lead rod containing a thermocouple for temperature monitoring. The expansion volume is visible near the top.

The SINQ-rod target is routinely used for a period of 2 years receiving a total beam charge of the order of 10 Ah or a peak charge density of 200 mAh/cm^2. The concept is expected to be able to cope with a beam power well above 1 MW, albeit with continuing optimization of its design parameters. It is also a perfect example, how the target itself can be used for extensive materials research: From Target Mark-II on, a number of its pins were not neutron production pins, but were test pins containing materials specimens of a large diversity for irradiation under the most realistic conditions. This SINQ Target Irradiation Program (STIP) has greatly contributed to a continuous improvement of the materials data base for spallation systems in the past and is continuing to do so, hopefully also in the future. Most of this work was reported in the various IWSTM meetings and the most recent updates can be found in this volume [23,24]. The value of such a research opportunity can hardly be over-stated.

5. Liquid metal targets

Liquid metal targets, which excel through the attractive features of not being susceptible to radiation damage in the target volume and allowing one to move the heated target material away from the beam interaction zone to extract the heat elsewhere, have always intrigued the designers of high power spallation neutron sources. This was true for the Canadian 60 MW_b ING project [25] as well as for the German 5.5 MW_b SNQ [10] and for SINQ (1 MW_b), ESS (5 MW_b), SNS (1.4 MW_b) and JSNS (1 MW_b) alike. While the first three were looking at PbBi (LBE) as target material, ESS [26], SNS [27] and JSNS [28] opted for mercury.

5.1. The mercury targets for ESS, SNS and JSNS

One important problem in the design of a liquid metal target is adequate cooling of the "window" in the container through which the beam enters the liquid metal. ESS, SNS and JSNS chose different flow configurations to ensure this cooling. The ESS design (Fig. 4) has three inlet channels, one from the bottom to establish the flow across the beam window and two on the sides to provide the balance of the mercury flow required for heat removal. In the SNS target (Fig. 5) only two inlet channels are provided which may result in a flow stagnation point or a region of low flow velocity at the

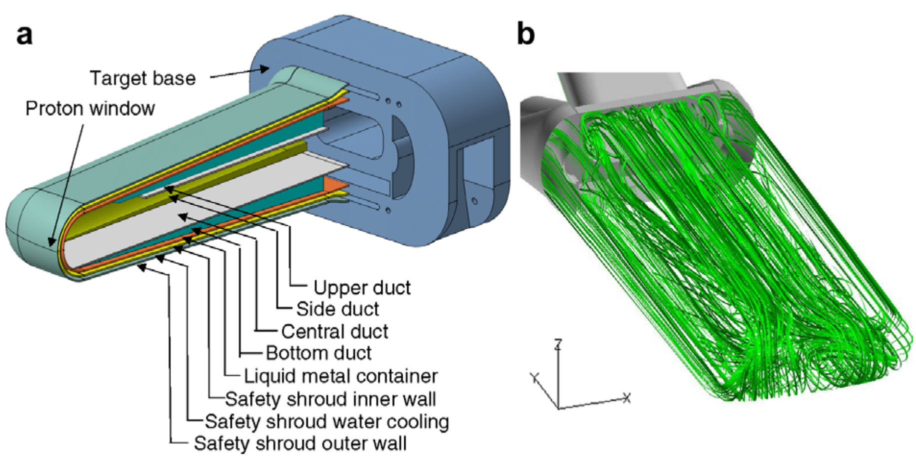

Fig. 4. The ESS mercury target design. (a) Mechanical configuration with inlet channels at the bottom and both sides, (b) flow simulation for 40% inlet flow through the bottom duct and 30% through each side duct.

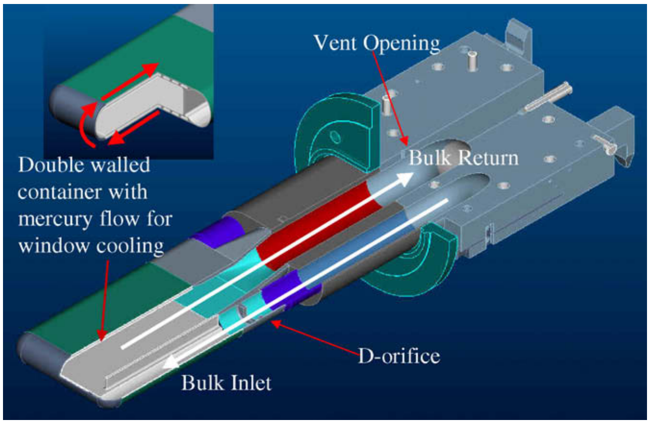

Fig. 5. The SNS mercury target design with inlet flow on both sides and bulk return flow through the target body. Window cooling is by means of a bypass flow in the container wall.

beam window. In order to ensure adequate window cooling at all times, the top and bottom walls and the front face of the target are double-walled with a bypass stream of mercury flowing in the interspace. Finally, for the JSNS target (Fig. 6) a horizontal cross-flow configuration was chosen with the bulk inlet flow on one side and the outlet flow on the other. A system of carefully designed vanes ensures that sufficient flow velocity is established at the beam entrance window.

Since in all three designs there is a risk of a window failure, each of the targets is surrounded by a double-walled water cooled shroud (only shown in Fig. 5). The enclosed interspace is monitored for signs of mercury or water leakage into it. In this way failure of the mercury container is not an accident but a normal operational event indicating the definitive end of the container's service life. This is an important feature because at present there is no way to predict the service life of the container based on solid experimental evidence.

The main problem short pulsed spallation sources with liquid metal targets are facing right now is the issue of cavitation erosion resulting from pressure waves in the targets after the instantaneous deposition of a large amount of energy. This problem has been – and still is – the subject of extensive experimental and theoretical research [29,30]. Cavitation bubbles forming near the container wall during the depletion phase of the pressure wave collapse violently forming an inward directed high speed jet. When this jet hits the wall, local hardening and embrittlement occurs and after some incubation period material begins to be removed from the wall ("cavitation erosion"). The problem is not only a reduction of the wall thickness (which must be small for reasons of heat removal and thermal stress to begin with). Also crack initiation has been observed during off-beam experiments. It is expected that this might lead to a significant reduction of the fatigue life of the wall. Finding a cure for this problem is of paramount importance in order to make operation of liquid metal targets in high power pulsed sources affordable – or at all possible – in the long run. Surface hardening was found to lengthen the incubation period by about a factor of 10, (from 10^6 to 10^7 pulses) but is not a fundamental cure for the problem. Fortunately it could be shown that flow at the wall has a positive effect, but hope for a long term cure rests on the injection of gas into the mercury, either in form of a "curtain" on the wall (cooling issue!) or of micro-bubbles of suitable size (<100 μm) and distribution (>0.5 %) in the volume.

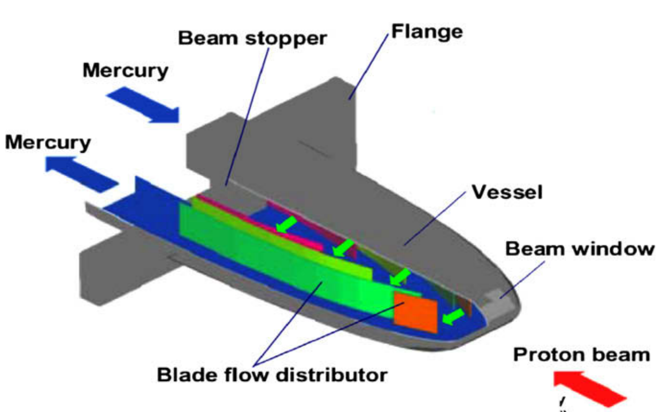

Fig. 6. Schematic of the JSNS mercury target with cross-flow window cooling. The flow distribution from left to right in the target is controlled by carefully optimized guide blades.

5.2. The PbBi-target experiment at SINQ (MEGAPIE)

SINQ, a continuous neutron source, depends on low neutron absorption for a high flux in the moderator, which is why mercury with its high thermal neutron absorption is not a suitable target material. On the other hand, a liquid LBE-target has been part of the SINQ development plan from the very beginning (see e.g. [31] and theoretical assessments [32]) had shown that such a target held the promise of a substantial gain (ca 60%) in neutron flux over the rod target with Pb-pins in steel canning described above. Due to the acknowledged complexity of a liquid metal target that would fit the SINQ geometry it was clear that a pilot experiment could only be carried out in an international collaboration. External interest in such collaboration arose from the desire to demonstrate the feasibility of a PbBi-target in the context of development efforts for industrial accelerator driven systems (ADS). The project was launched in 2000 [33]. It triggered a large research effort relating to liquid metal corrosion, liquid metal embrittlement by PbBi and radiation effects in structural materials. The design of the target was carried out by SUBATECH from Nantes (France) in close collaboration with PSI. Much of the manufacturing and assembly work was done by ATEA, Nantes under supervision and quality assurance by PSI. Construction of this target (Fig. 7) was a real challenge because all components in contact with the liquid metal had to be enclosed in a container that fit in the space previously taken up by the rod target. While the well proven material ALMg3 was retained for the outer, water cooled container, the lower liquid metal container was made from the martensitic steel T91 and the components in the upper half of the target, mainly the 12 pin heat exchanger, the off-gas plenum and the EM-pumps as well as the lower flow guide tube and central rod were made from austenitic steel. In view of the low maximum temperature in the target and limited envisaged operating period no provisions were made to actively control the oxygen level in the PbBi. It had originally been discussed to include radiation effects specimens in the central rod but in the end this plan was abandoned in favor of testing a newly developed neutron flux monitoring system.

An important feature, which affected not only the design of the target, but also its heat removal system was the fact that the LBE had to be kept liquid during the whole period of operation in order to exclude possible damage to the structures from the slow expansion of solidified PbBi, which is a well known effect. The possibility of draining the liquid metal from the container in situ had been abandoned due to spatial constraints in the room above the target and in view of licensing difficulties.

The MEGAPIE target was operated over a period of four months with a proton beam current of up to 1.35 mA and a total

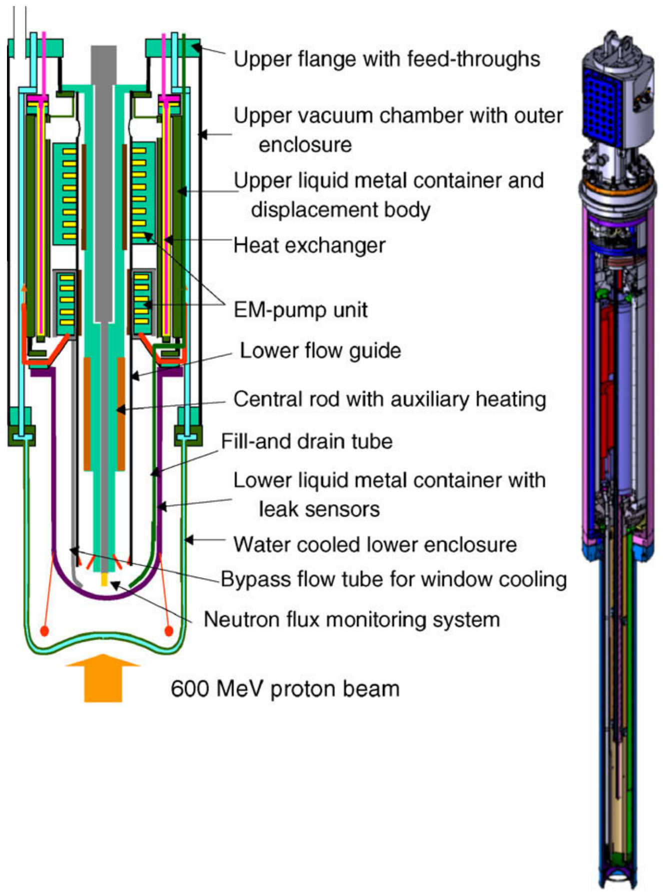

Fig. 7. The MEGAPIE target. Left: schematic, showing the arrangement of its main components; right: representation of the engineered target.

accumulated charge of 2.8 Ah (a value similar to the one for the rod target Mark-I). Details on the operating conditions and experience may be found in Ref. [34]. The measured flux gain in the reflector relative to the previous rod target was 1.8, which is in good agreement with the value of 1.6 quoted above, taking into account that this value was for an all lead target, whereas the actual reference target contained a large number of experimental rods with test samples which caused a flux depression of 10%. The target was taken out of service in December 2006 and is now awaiting post irradiation examination [35]. While a somewhat longer irradiation period might have been desirable, the MEGAPIE project may still be considered a success because it demonstrated, for the first time, that a LBE-target can be operated in a MW-class proton beam.

5.3. The windowless PbBi-target for MYRRHA

Clearly, the proton beam entry window of a liquid metal target is its most critical component and therefore studies towards windowless targets were carried out by several research teams in the past (see, e.g. [25,10,36]). The concept involves a converging hollow flow of liquid metal with a coalescence point at the position of the target head. Such a target is now actively pursued for the proposed fast neutron irradiation facility MYRRHA in Mol, Belgium [37]. One of the issues is that it obviously requires beam injection from above. Obtaining a stable target surface with minimal recirculation is another big challenge. Since such recirculation cannot be reliably excluded, MYRRHA is intended to operate with a "hollow" proton beam to minimize heating in the target center (see insert in Fig. 8).

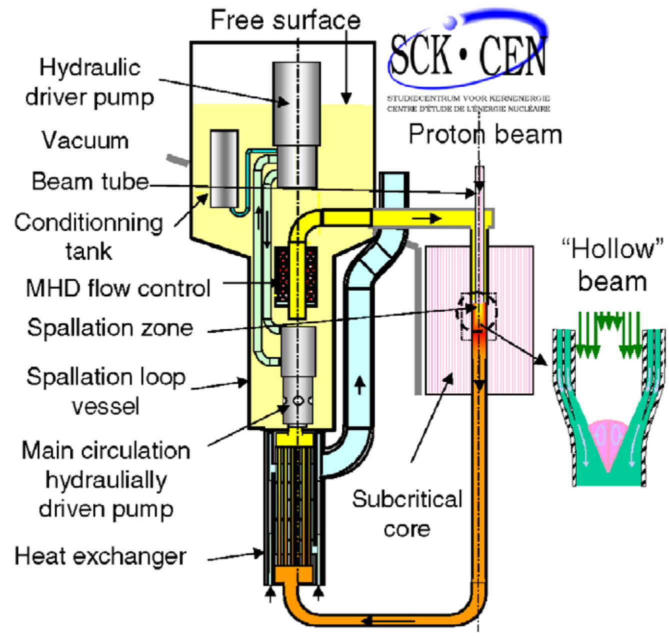

Fig. 8. Schematic of the MYRRHA spallation target loop.

The planned beam parameters are 2.2 mA at 600 MeV, which is about twice the power level of MEGAPIE[2]. The spallation target with an outer diameter of 10 cm will be located in the center of a sub-critical reactor core and will be exposed to its fast neutron flux level of 10^{15} cm^{-2} s^{-1}. In addition the wall will be exposed to fast neutrons and protons from the spallation zone. This extreme radiation environment, together with the elevated operating temperatures of more than 300 °C and the fact that it will be in contact with rapidly flowing LBE will require a careful materials evaluation and qualification program. Frequent exchanges of this part of the loop will, nevertheless be necessary.

The MYRRHA spallation loop (Fig. 8) will be completely inserted in the LBE reactor cooling loop, which will also serve as a primary coolant for the spallation loop. The LBE-to-LBE heat exchanger will be located below the main spallation loop vessel with the hydraulically (LBE) driven main circulation pump arranged directly above it. The purpose of the main circulation pump is to maintain the level difference between the free target surface and the spallation loop vessel. This level difference is, in turn, the driving force for the flow into the target tube. An MHD pump which can accelerate or decelerate the LBE serves to control this flow. Since most of the spallation loop is located in a region of moderate radiation level, a reasonably long service life of its components is anticipated.

A problem which needs close attention in LBE loops with extended service life is oxygen concentration C_O in the LBE. It must be low enough to prevent oxidation of the LBE but high enough to avoid destruction of the protective oxide layer on the walls. A C_O-level of 10^{-6}–10^{-7} wt.% must be actively maintained because significant amounts of hydrogen and other oxygen trapping species are produced in the spallation process. This topic is the subject of active ongoing research and of various papers in this workshop.

[2] In fact, for a potential upgrade to an experimental ADS facility under discussion (MYRRHA/XT-ADS) an increase of the beam current to 3 mA or more might be necessary.

6. Rotating targets

6.1. The SNQ design and development effort

In an effort to ease the problems of heat removal and radiation damage in the target as well as its structural materials, a rotating target was considered when the first 5 MW spallation source project (SNQ) was started in Germany in 1979 [31,38]. The original concept foresaw a target disc supported from underneath with the water coupling, support and drive (CSD) unit located in a cave beneath the target block, where hands-on maintenance would be possible. For replacement the target would be moved horizontally into a hot cell. During the subsequent engineering design efforts a solution was favored, in which the target was mounted directly on the CSD-unit which sat on the target trolley. Fig. 9 shows the target and its CSD-unit. Rotation of the target was to be effected by a water turbine and target levitation was by a hydrostatic water bearing. Both were fed by pressurized water which drained into the main coolant flow. A lubrication free roller bearing was chosen for radial stabilization. For target exchange the trolley was to be moved into the hot cell where the target could be detached from the CSD-unit by remotely loosening the bolts labeled “8” in Fig. 9.

The CSD-unit shown in Fig. 9 is the design Nr II, which was conceived taking into account the experience gained from operation of a full scale prototype over several months. The main alterations were: replacement of a radial turbine by the axial one to facilitate remote replacement, change from the hydraulic radial bearing which was found to be somewhat temperature sensitive to a roller bearing and a new design of the water-to-vacuum seal.

The target disc was to be made up of clad rods as discussed above in Section 4. The support structure was of AlMg3 alloy. Since practically no information was available on the radiation damage in this material under spallation conditions a very large target diameter of 2.5 m was chosen. Extrapolation from the experience that has in the mean time accrued from the operation of the SINQ targets shows that, from a radiation damage point of view the target could probably have survived in excess of 200,000 full power hours. This clearly shows that a smaller diameter optimized for heat removal would have been sufficient.

During the later phase of the SNQ project an alternative solution of a disc made up of closely packed hexagonal tungsten rods and cooled only through the top and bottom support plates was considered. The goal was to optimize neutron production and minimize radiation effects in the coolant (spallation of oxygen, production of ^{7}Be and positron emitters, as well as radiolysis) [39]. While, based on materials properties of tungsten in the non-irradiated state the concept looked very promising, more information on radiation effects at temperatures around 400–500 °C would be needed for a final assessment, e.g. as an alternative solution for ESS.

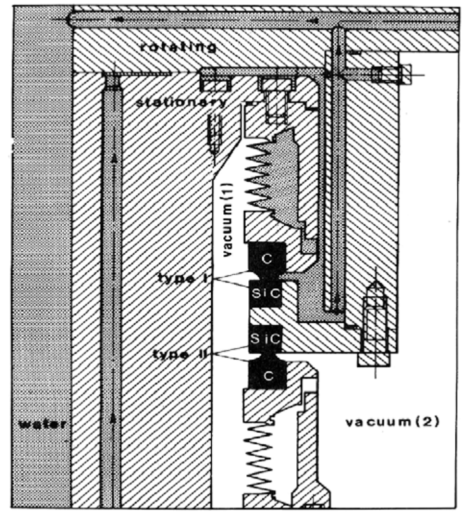

Fig. 10. Schematic of the sealing system for SNQ CSD-unit type II. The stationary parts are hatched from top right to bottom left, the rotating parts from top left to bottom right. Water filled volumes are indicated by gray shading. Seal type I is of mixed friction, seal type II is dry.

Although the CSD-unit as shown in Fig. 9 is very compact and its predecessor has been tested in out-of-beam conditions, some uncertainties remain about its service life due to lack of information on the materials foreseen in particular for the water-to-vacuum sealing system. A simplified sketch of this system is shown in Fig. 10. (from Ref. [17]). A double slide ring sealing was foreseen, made up of a hard material (SiC) fixed to the rotating part and a softer one (C) which would remain stationary. This means that the SiC rings would be irradiated uniformly due to the target rotation, while the C rings would receive unequal loads on the sides near and far from the beam interaction zone. Although the radiation levels at the position of the seals are comparatively low relative to the beam interaction zone there is practically no dilution effect from the target rotation. The behavior of these seals under irradiation remained one of the major concerns in the concept. A program to obtain relevant data by carrying out experiments at Los Alamos was abandoned when the SNQ project was terminated in 1985.

6.2. Rotating targets for CSNS and SNS

After more than 20 years sleeping beauty seems to be awakening again, triggered by a proposal for a regional medium power spallation source in the Basque Country [40,41]. The idea here was that, by using a rotating target of some 50 cm diameter in a medium power (500 kW) spallation source, a service life of several decades was achievable. Using a vertical insertion concept with an

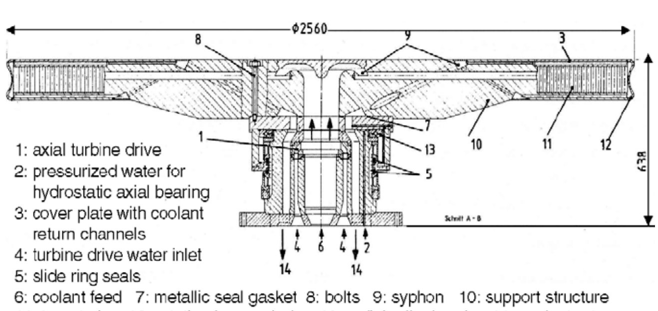

Fig. 9. The SNQ rotating target on its CDS-unit type II.

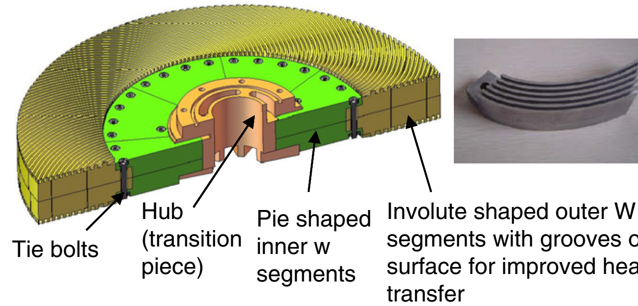

Fig. 11. Target disc of the CSMS rotating target. The insert shows a prototype piece of the involute shaped W segment with grooved surface.

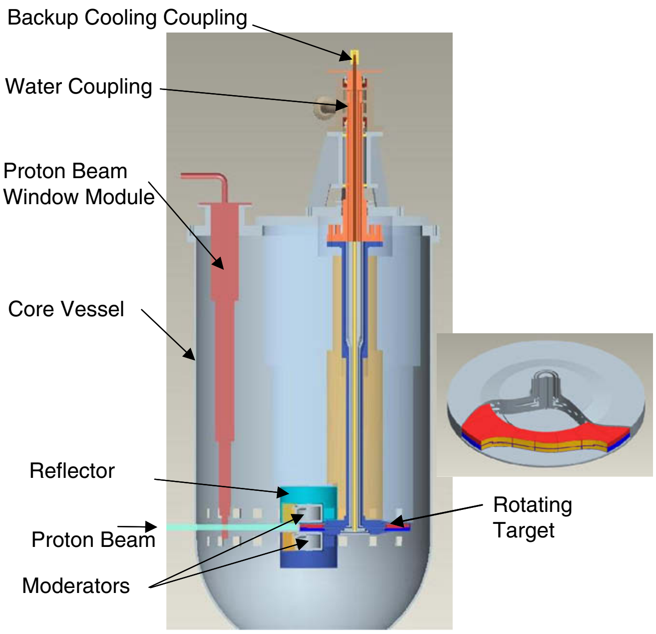

Fig. 12. The SNS rotating target arrangement and disc.

exchange flask as in SINQ, this would allow designing the facility without a hot cell attached to the target block and thus help to save on initial construction cost and free an angular range in the forward region of the target block for placement of a neutron guide bundle.

The same concept has been picked up by the CSNS project and is now being actively pursued [42]. The target is conceived as a flat cylinder of tungsten with internal subdivision to reduce thermal stresses and with a grooved surface in the outer 10 cm of its top and bottom surface to improve heat transfer to the coolant (Fig. 11).

The outer target region is made up from involute shaped W segments with opposite curvatures in the top and bottoms half of the target. The target will be essentially surface cooled, thus providing the most compact primary neutron source possible. Although water in direct contact with the W will only be hit by protons when flowing across the cylindrical surface and only in a fraction of the circumference, it may still be necessary to apply some kind of protective coating. This question and potential candidates for a coating are still under investigation.

The target will be mounted in a target shield plug of little more than 50 cm diameter and can be inserted in the target block from above [42]. Coolant connections support and drive unit will be located on the top of the plug, which will allow complete hands-on maintenance of these components.

A similar arrangement has been chosen for the rotating target under study at SNS for its second (long pulse) target station [43]. Fig. 12 shows the general arrangement. The target is hanging by a 3.4 m long shaft from its CSD-unit which is located on the top of the target block. Being designed for a beam power of 3 MW, the target disc has a diameter of 120 cm and weighs about 1.3 tons. The central part and the water containing shroud are made of steel and the 25 cm deep and 7 cm thick outer ring is made of pie shaped W slabs clad with 2 mm Ta. Cooling water flows outward over the top and bottom surfaces and is returned through a gap in the central plane of the target disc.

Thermal hydraulic and mechanical design studies carried out so far have produced very promising results and construction of a mock-up test stand is planned for 2009. From a neutronic point of view the target is expected to perform equally well or better than a liquid mercury target of the present design.

7. Concluding remarks

As spallation neutron sources are now heading up to the 5 MW beam power level, target issues are getting more and more serious. While there are several concepts which hold a promise to cope with these thermal and radiation loads, there still remain a lot of materials R&D to be done to arrive at reliable predictions for the target service life and to minimize waste from spent target modules. In particular pulsed operation of the sources adds to the need for reliable data because, while no influence is expected on the radiation effects in the material, mechanical load levels depend strongly on pulse power and duration. The use of liquid metal targets, in particular PbBi, brings along a new class of problems related to corrosion and erosion effects and to sensors to measure oxygen concentration. It is, therefore, of paramount importance that irradiation opportunities be provided in existing facilities wherever possible until new opportunities such as the Materials Test Facility under design at Los Alamos [44] or eventually MYRRHA become available.

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