DEVELOPMENT OF HIGH POWER TARGETS

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Abstract

High power targets are at the very heart of most applications of accelerators to science and technology. With many projects aiming to utilize beams in the multi-megawatt power range, solid targets, in particular stationary ones, become increasingly difficult to cool. Liquid metal targets are often the concept of choice. Designs range from fully enclosed systems for neutron generation to free jets to allow extraction of low energy–highly ionizing radiation (pions and muons). Mercury is often the preferred target material due to its liquid state at room temperature and other favourable properties. For designs aiming at high temperature operation or depending on small neutron absorption PbBi is the preferred target material. Liquid lithium is proposed for a deuteron stripping target for the IFMIF project. Issues to be solved include solid-liquid metal reactions, radiation effects, general liquid metal technology, handling of spallation products as well as design of components and subsystems. In addition, short pulse operation leads to the generation of pressure waves inside the targets and to the need to control their consequences.

INTRODUCTION

High power accelerators up to several Megawatts of beam power (MW_b) are now under construction or in a detailed stage of planning all around the globe. Their designated applications span a wide range of scientific and technological fields from very fundamental questions to be investigated by neutrino physics and radioactive ion beams via various scientific and technological applications of neutrons all the way to technological issues including the final treatment and disposal of long lived radioactive waste from nuclear power generation. Despite large differences in the goals and techniques used to generate the desired type of radiation in these projects they have a common need to use condensed matter in the beam, the so called targets, to convert the accelerated particles, mostly protons, into the desired radiation. A high density of the secondary particles produced ("bright source") being an important design parameter, common issues in all high power targets are heat removal from and radiation damage in the materials used. The present paper will give an overview of approaches taken to solve or circumvent these limitations, which are particularly serious when short pulses are required to accomplish the scientific mission.

SOLID TARGETS

The Rotating 5 MW_b SNQ Ttarget

When in the early 1980ies the first pulsed spallation neutron source in the multi-megawatt beam power range was proposed and studied in detail (the SNQ project [1], [2]), it was clear that or the goal of a 5 MW_b spallation target could hardly be met by a water cooled plate target as developed for the then existing low power sources IPNS [3], and ISIS [4]. Although a liquid metal target as originally proposed in the Canadian ING-Project (60 MW_b, [5]) was studied as an option the then preferred concept borrowed an idea used for high power X-ray anodes: allow the target to rotate in order to dilute the average load on the material. The design, shown in Fig 1, foresaw a 2.5 m diameter disk of 12 cm height. whose internal structure in the outer 70 cm was made up of lead filled aluminum alloy tubes which would be cooled by water flowing between them. This water would flow forward through bores in the upper and lower support structure of the disk and would, upon turning around, also cool the rotating beam entrance window. The support structure, the beam window and the tubes of the target elements were to be of the alloy AlMg3.

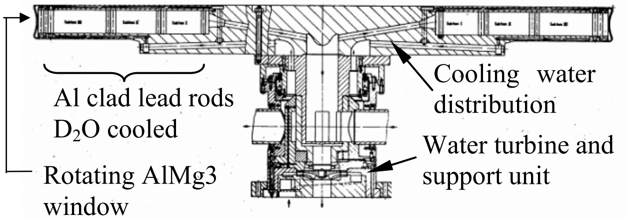

Figure 1: The SNQ rotating solid target concept [1]

With a diameter of the target pins of 2.5 cm in the outer region and a water flow gap of 1.5 mm between them the degree of filling was much higher than what could have been achieved in a stationary system. The speed of rotation was to be such that consecutive pulses of the (100 Hz) accelerator would hit adjacent areas on the target periphery, requiring ca. 8 m/sec or, with a circumference of 7.8 m, a rotation frequency of about 1 Hz. This very moderate rotation rate was to be accomplished by a water driven turbine which would be fed from a controlled pressure loop and which would drain into the main cooling water circuit. Similarly, levitation of the target would be by pressurized water flowing through a narrow radial gap. In this way nearly friction free rotation (apart from a labyrinth sealing between the stationary and the rotating parts) could be accomplished. A model of the target support and drive unit was built and with a dummy target load simulating the weight and inertia of the actual target, was run for nearly 1000 hours without problems, albeit in the absence of radiation load.

Two alternatives to the lead filled aluminum tubes were considered for the target structure: clad depleted uranium rods and an edge cooled array of hexagonal tungsten rods.

While uranium was expected to yield nearly 2 times more neutrons than lead, its use was discarded on the basis of waste considerations because, although the rotating target kept most of the material outside the region of high thermal neutron flux, production of plutonium and other higher actinides could not be excluded. This would generate a much more serious licensing and disposal problem than lead, in which virtually no long lived alpha activity is generated.

On the other hand, an edge cooled tungsten target [6], appeared as a very attractive solution because it would allow a more than 50% higher target density than surface cooled lead pins and would largely avoid the difficulties resulting from radiolysis and formation of ^{7}Be in the water hit by the proton beam. As the SNQ project was terminated in 1985 the research necessary to qualify the edge cooled tungsten target never got done.

The concept of a rotating solid target also formed the backup solution for the 5 MW$_b$ ESS target (see below) in case there were problems with the liquid metal target that could not be solved satisfactorily. For the 50 Hz pulse repetition rate a diameter of 1.5 m was chosen, leading to a slightly higher time average radiation load. This was considered acceptable since, in the mean time, experience accrued in the operation of SINQ (see below) indicated that the service time of the beam entrance window and pin walls would still be more than 75 000 hours. Again, an edge cooled tungsten version was considered more desirable, but was also recognized as needing more preparatory R&D work.

The Stationary 1 MWb SINQ Target

While the SNQ target never got a chance to be demonstrated in a real facility, a target of basically similar design, albeit stationary in the beam has been shown to be a robust and versatile concept in the Swiss spallation neutron source SINQ at the Paul Scherrer Institut [7]. The original concept for this 1 MW$_b$ class facility foresaw a liquid PbBi metal target cooled by natural convection [8], which is one of the reasons why the beam in this facility is injected into the target from below. After the project had been approved this idea was abandoned for a variety of reasons, an important one being the undefined conditions during start up after a beam trip or shutdown: While the natural convection flow had to be established by carefully controlling the beam intensity over an extended period of time, the window cooling conditions were still not well defined. The target concept finally chosen for SINQ (Fig 2) is an arrangement of rods surface cooled in a cross flow configuration similar to the one developed for SNQ. The ca. 50 cm long metal support frame holding a bundle of rods forms the lowermost part of a 4 m long structure whose outer shape is reminiscent of the original liquid metal "bottle". It is surrounded by a double walled and separately cooled shell of AlMg3, which serves as a cooling water container (Fig. 2b). The cooling water flows downward between the target frame and this container, turns around at the bottom and cools the target rods as it flows upward between them.

A special feature of SINQ relative to other spallation neutron sources is its operation in a continuous (non pulsed) mode like a reactor, which prohibits the use of strongly neutron absorbing materials in and around the target in order to ensure a high stationary neutron flux in its large heavy water moderator tank. While solid Zircaloy rods had been chosen for the first two target units used, the change to the current production version with lead rods in thin stainless steel tubes yielded about 50% more neutron flux in the surrounding large heavy water moderator. The latest target used has been exposed to a total charge of more than 10 Ah, without any problem. This corresponds to about 20 displacements per atom (dpa) in the most highly loaded stainless steel tubes. Except for gas production radiation damage in the lead is not a problem due to the high operating temperature. During full power operation part of the lead in some of the rods is most likely molten.

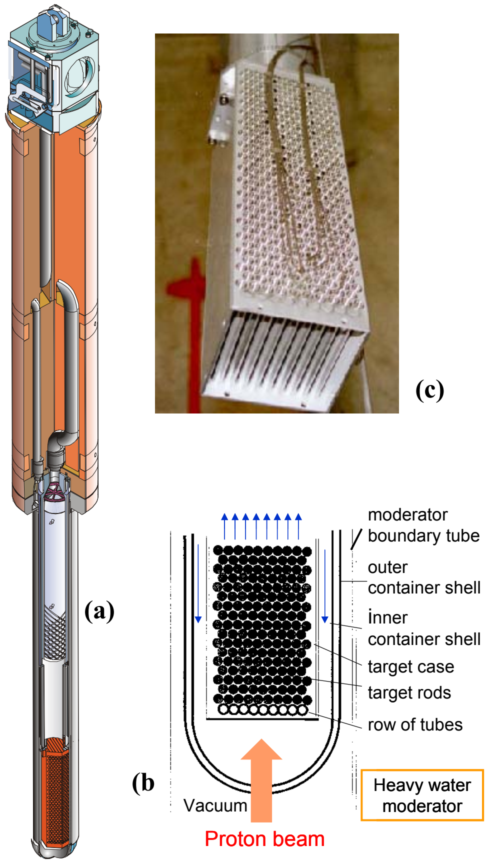

Figure 2: The SINQ solid target
- (a) overall view showing the target rod array and the upper and lower shield plugs
- (b) Schematic of the target rod array with double walled and separately cooled shell
- (c) Rod array of Target Mk 3 (lead in stainless steel tubes; front row: emptyAlMg3 tubes). Some rods are test units with thermocouples

A very important feature in the operation of the SINQ target is its associated radiation effects program STIP (SINQ Target Irradiation Program) [9]. Up to 20 of the total of 450 target rods are actually experimental test capsules filled with different kinds of test specimens which range from 3 mm diameter TEM discs via miniature tensile probes all the way to liquid metal (PbBi and Hg) filled capsules or even massive rods of alternative materials.

ENCLOSED LIQUID METAL TARGETS

The First Step: The MEGAPIE Project

Being, by a large margin, the world's most powerful spallation neutron source and having the flexibility for materials research SINQ is an important test facility on the way to more powerful targets. This is even more true when looking at the latest move to develop a liquid metal target [10], [11] (which SINQ was originally designed for, as mentioned above). The project, called MEGAPIE (**MEGA**watt **PI**lot **E**xperiment) is supported by a large international collaboration interested in the development of liquid metal targets for ADS but is also of interest for SINQ itself, because it is expected to increase its neutron flux by another 40 –50% [12], mainly due to the higher average density, the reduced amount of structural material and the absence of water in the beam. In contrast to the original concept, MEGAPIE will be a fully pumped target. The PbBi loop will be completely enclosed in the target shell. An electromagnetic pump will drive the main flow of liquid metal through the neutron producing zone and the heat exchanger. In order to ensure good cooling of the proton beam entrance window (at the bottom of the target) a bypass flow driven by an electromagnetic auxiliary pump will be directed across the window, thus establishing a well defined flow velocity at all times, which was shown to improve the window cooling by a factor of five [13].

Although it is known that, at elevated temperatures it is necessary to carefully control the oxygen content in a PbBi loop, MEGAPIE does not feature such a system because it is intended to run below 400°C at all times and everywhere in the loop. Apart from this, MEGPIE will, for the first time, demonstrate all auxiliary systems required to operate a liquid PbBi target, including an intermediate organic fluid cooling loop. Post operation analysis after the end of the intended 1 year service time will give important information for the design of future PbBi target systems as they are mainly intended to be used in ADS facilities for nuclear waste transmutation. This includes in particular the production and release/retention of alpha-active polonium isotopes, which are one of the major safety issues in this type of target.

The MEGAPIE target features a double walled and separately cooled outer containment shell with a leakage monitoring system that would shut off the beam immediately if PbBi would enter the interstitial space. Nevertheless, in the interest of continued SINQ operation, extensive precautions were taken to be able to recover from the consequences of a simultaneous breach of all three containment shells.

Since it is not intended to drain the liquid metal from the container during extended shut down periods, the PbBi must be kept in the liquid state at all times because it is known to expand after solidification, which might damage the target structures. This is accomplished by a combination of auxiliary heating systems and by carefully controlling the heat removal rate through the organic coolant loop.

Mercury Targets For Pulsed Spallation Neutron Sources

PbBi is the preferred target material in systems where neutron absorption must be minimized in order to obtain a high time average neutron flux or where, as in power generating systems, a high operating temperature is desirable. Since both is not the case in the upcoming class of pulsed spallation neutron sources, these facilities prefer mercury as a target material, mainly because it does not require auxiliary heating, has a higher density than PbBi and does not produce alpha-active isotopes.

The concept was first proposed [14] for the 5 $\mathrm{MW_b}$ target of the European Spallation Source (ESS) [15] and was then adopted and slightly modified for the USA SNS [16] and the Japanese JSNS [17] projects. All three concepts are based on horizontal beam injection and a laterally extended ("slab") target geometry. Apart from having different flow rates due to different design power levels (ESS: 5$\mathrm{MW_b}$, SNS: 2$\mathrm{MW_b}$, JSNS:1 $\mathrm{MW_b}$) the three targets differ mainly by the way in which the flow is directed across the window. ESS follows essentially the MEGAPIE philosophy to direct part of the flow across the window by providing a bottom inlet channel in addition to two side inlet channels. The SNS team decided to use a double walled container with a narrow channel to guide a partial flow all the way across the window and out of the target again (Fig. 3), while the JSNS group developed an elaborate system of blades to establish a horizontal flow across the window and in the whole beam interaction zone. The design of all three systems is well advanced and supported by extensive fluid mechanics and thermal hydraulics calculations.

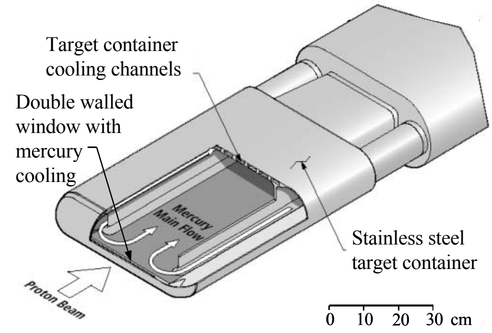

Figure 3: Schematic representations of the SNS mercury target

All three targets have separately cooled outer shells (not shown in Fig. 3), which serve to safely retain the mercury in the system in case the primary liquid metal container develops a leak. The targets are mounted on movable carts which allow to retract them into maintenance cells for shell replacement after draining the mercury into a storage tank.

A problem not present in continuously operating targets arises from the very concentrated energy input into the liquid metal during the short duration (ca. 1 µsec) of the pulse in these sources. This time is too short for the liquid metal to accommodate the thermal expansion of the heated fluid zone. As a consequence a pressure wave is triggered which travels outward and sets up high tensile stress in the container wall. During the rarefaction phase of this pressure wave cavitation bubbles develop in the fluid, since the liquid cannot sustain tensile stress. This leads to the well known effect of pitting erosion on the container when the bubbles collapse and eject a high velocity jet near the wall. This phenomenon was carefully studied in out-of-beam tests [18]. as well as in in-beam tests [19] at relevant pressure or power pulses. If left unmitigated, it might lead to unacceptably short life times of the target shells, of the order of three weeks or less. While surface hardening was found effective in delaying the onset and progress of the erosion process, this treatment only affects a thin (30 microns) surface layer and cannot be considered a dependable cure for the problem. A solution might be to increase the effective compressibility of the liquid metal by injecting finely distributed bubbles as proposed early on, when the problem was fist recognized [20]. Small bubbles in the fluid affect pressure waves in two ways: A small amount of bubbles of the right size strongly attenuates travelling sound (pressure) waves, while a larger fraction of bubbles (ca 1% in volume) provides enough "expansion space" to reduce substantially (up to a factor of 1/1000) the build-up of pressure in the bubbly liquid. An international collaboration is working to develop a method that will allow to produce the right size and quantity of bubbles in a mercury target.

WINDOWLESS LIQUID METAL TARGETS

While liquid metal targets have the advantage of high heat removal capability and absence of radiation damage in the volume, their main limitations are cooling (flow rate) requirements and radiation damage in the beam entrance window, even if the pressure wave issue can be solved or plays no role (as in continuously operating sources). Since the times of the ING project in the early 1960ies [5], source designers have therefore embraced the idea of injecting the beam directly into the liquid metal without a target window. Both, parallel flow (with the beam injected parallel to the flow direction of the liquid metal) and cross flow configurations have been considered.

The latter is the preferred solution of the IFMIF project [21] which aims at providing a high flux of neutrons with spectral properties near to those prevailing in a fusion reactor first wall by stripping 2x125 mA of 40 MeV deuterons of their protons in a flowing lithium target. In this concept, which uses a horizontal beam, a "curtain" of lithium flowing downwards is pushed against a curved back wall by centrifugal forces to establish sufficient internal pressure to prevent boiling and good heat contact to cool the back wall. This would not be possible for the front wall due to the very high heat deposition of the low energy deuterons in the solid material. A concept of this kind requires very high flow rate of the liquid metal and is possible only if the range of the injected particles, i.e. the required target thickness is small.

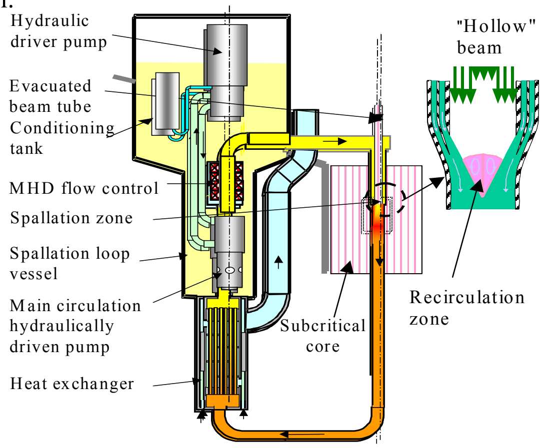

Figure 4: The MYRRHA spallation target

For particles with a longer range injection of the beam parallel to the direction of the liquid metal flow allows to take advantage of a higher temperature rise in the liquid and hence smaller flow rates and heat exchangers. This configuration is the preferred solution of most ADS studies. A project which is actively developing this concept is MYRRHA, a high flux fast neutron irradiation facility proposed by SCK·CEN at Mol, Belgium [22]. As in an ADS facility a spallation target will be used to drive a PbBi cooled sub-critical core which will then generate the high fast neutron flux to be used for the planned experiments [23]. MYRRHA is planned to be fed by an accelerator of 350-400 MeV with a beam current of 4-5 mA. It is mainly this low proton energy which prompted the MYRRHA designers to embark on a windowless PbBi target design with beam injection from above. A schematic representation of the loop is shown in Fig. 4. The flow through the target is driven by the hydrostatic pressure due to the level difference between the surface of the PbBi reservoir and the target position, The flow rate can be increased or decreased by an auxiliary MHD pump that can operate in forward or reverse direction with varying power. The heat exchanger is arranged in the return flow in front of (below) the main pump that maintains the liquid metal level in the reservoir. Due to unavoidable leakage to the main core cooling loop, which is also PbBi, the main pump is hydraulically driven by a flow of PbBi which is generated in a hydraulic driver pump above the level of the reservoir.

The MYRRHA target configuration is being investigated both experimentally and numerically. Full scale experiments with mercury and model calculations with varying the parameters revealed two problems with the configuration shown in Fig. 4: (a) there is always a re-circulation zone forming at the point of coalescence of the hollow liquid metal flow, and (b) there is a risk of cavitation due to a low pressure region created near the walls. Both problems were also recognized in a rather comprehensive study for windowless targets for higher power (and hence larger cross sections) [24]. The authors found that a certain gas pressure level had to be maintained above the target to suppress the re-circulation zone, which they proposed to establish by a supersonic gas jet. For MYRRHA it is foreseen to use an intensity distribution in the proton beam that minimizes heat input in the re-circulation zone ("hollow beam"), as shown in the insert in Fig 4.

A similar target was also studied in the German SNQ project [1]. A nozzle type outlet was developed to allow the hollow jet to coalesce without lateral confinement. While the concept was successfully demonstrated for a reduced scale, it is not clear whether a target with a diameter of 10 cm or more can be operated in this way.

AN UNCONFINED LIQUID JET TARGET

The concept of a coalescing hollow jet is also the ruling idea in the target system considered for the next generation radioactive beam facility (EURISOL) [25]. Here it is proposed to inject a beam coaxially into a mercury jet formed in essentially the way studied for SNQ but with a high speed pumped horizontal flow. The configuration is shown schematically in Fig. 5.

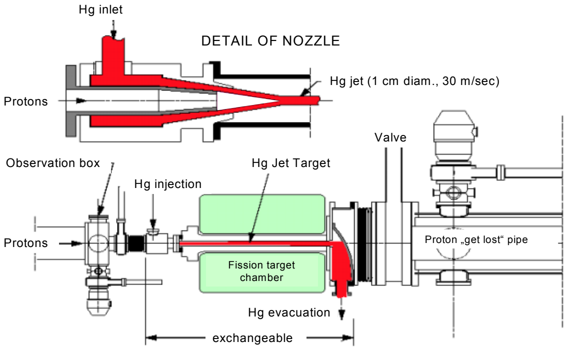

Figure 5: The EURISOL jet target concept

It should be noted that a target with a free surface is in principle not suited for pulsed high power operation because it will be destroyed at each pulse. Nevertheless consideration is being given to using a target of the design shown in Fig 5 also for the next generation neutrino factory (NuFact). The idea is to use a very high flow rate to restore the configuration between two pulses over the beam interaction length (ca 60 cm).

CONCLUDING REMARKS

Medium Energy Accelerators (around 1 GeV) are now reaching a power level of several Megawatts, which makes it increasingly difficult to devise condensed matter targets for efficient production of secondary particles. While solid, water cooled targets can be used up to 1-2 MW$_b$, liquid metal targets of various deigns are being considered for higher power beams. Their application, in particular in short pulse facilities does, however, still require a fair amount of R&D work.

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