HIGH POWER TARGETS FOR SPALLATION SOURCES

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ABSTRACT

Spallation, the bombardment of a heavy metal target by an intense beam of protons, has become an established technique for the production of high intensity fluxes of neutrons. There are, currently, proposals and design studies for a variety of high power sources covering an increasing range of applications such as energy production, transmutation of radioactive waste and tritium production facilities as well as the second generation of neutron sources for condensed matter research. Design of the targets for high power spallation sources, with a beam power of several megawatts, presents a formidable technical challenge both in terms of heat removal and materials selection. The requirements and concepts for such targets are reviewed.

1 INTRODUCTION

Public concern over the operational safety of nuclear reactors, together with the problems associated with the long term management of radioactive waste, has made approval of new reactors increasingly difficult.

Considerable efforts have been made to investigate the use of accelerator based systems as an alternative in almost all areas traditionally covered by reactors. In particular these include:

- Thermal neutron beam sources
- Materials irradiation studies
- Isotope production
- Tritium production
- Transmutation of radioactive waste
- Power Generation

At present there are four operational thermal neutron beam sources: KENS KEK Japan 3 kW, IPNS ANL USA 7 kW, MLNSC LANL USA 60 kW and ISIS, RAL UK 160 kW. The SINQ source at PSI in Switzerland is expected to start operation later this year at 1 MW beam power and a 240 kW source is under construction based on the linac at the Moscow Meson Factory. The LANSC linac operates at 1 MW and the complex includes a materials irradiation facility.

Spallation sources generally employ a high intensity proton beam with an energy of, typically, 1 - 2 GeV although there have been proposals to use beam energies up to 10 GeV. All depend on the provision of an efficient target system to produce the high neutron fluxes required. The various uses impose, in detail, different requirements for targets. The main challenge for the target designer is to optimise the useful neutron production within the practical engineering constraints of heat removal and taking account of the radiation damage to the target and structural materials.

2 SPALLATION

The spallation process is illustrated in figure 1. The proton beam is incident on a heavy metal target which is, typically, about one range length long (30 - 60 cm.).

When a proton interacts with a target nucleus a few energetic particles are produced, leaving the nucleus in a highly excited state. The nucleus returns to the ground state by emission of neutrons, protons, deuterons, tritons and alpha particles - ‘evaporation’. The energetic particles go on to interact with other target nuclei producing more excited nuclei, and hence neutrons, in a nuclear cascade. The evaporation neutrons, with a typical energy of about 1 MeV, travel through the target material and those which escape from the target form the useful source for the applications listed above.

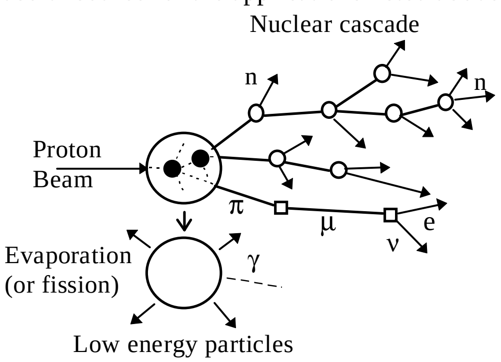

Figure 1. The Spallation Process

In many target materials the excited nuclei will undergo fission to leave two fragments which will de-excite by evaporation.

These processes deposit heat in the target, the majority from ionisation loss of the protons with some from the kinetic energy of the nuclear recoils. For targets where the amount of fission is small about 60% of the proton beam energy is deposited as heat. The heat deposited in a target with significant fission cross section is from 1.5 to many times the beam power, depending on the fission multiplication.

The nuclear interactions also result in damage to the target material and the production of considerable quantities of hydrogen and helium.

Several computer codes have been developed to calculate the complete physics of the spallation process and transport of the secondary particles. The most commonly used being based on the HETC [1] package. These have flexible 3 D geometry packages which allow the inclusion of full engineering details in the calculations.

3 TARGET MATERIALS

For a thick target the dependence of the yield of neutrons per proton as a function of proton beam energy (E GeV) and target material (atomic mass number A) is given by [2]:

$$\text{Yield} = 0.1\,(A+20)\,(E-0.12) \qquad (A< 238)$$
$$= 50\,(E-0.120) \qquad \text{(Fissionable targets)}$$

The desirable properties of a spallation target material are:

- High Atomic number
- High density
- High/Low melting point (solid/liquid)
- High thermal conductivity
- Chemically inert, low corrosion
- Resistance to radiation damage
- Low resonance integral for neutron absorption
- (Low absorption for thermal neutrons) see section 6
- Good availability and low price

The most important property is high atomic number to maximise the neutron production. The usual materials considered are tungsten and tantalum (and their alloys) for solid targets. Liquid metals considered have been lead, lead/bismuth eutectic and, more recently, mercury.

The advantage of a fissionable material is clear in this respect. To date targets made from uranium have been operated at KENS, ISIS (depleted) and IPNS (both depleted, D, and enriched, E). However, the problems associated with radiation damage have led to limited operational lifetimes [3] as shown in the table below. Metallic uranium is not suitable for high power sources.

Target	Lifetime MWdays	Target	Lifetime MWdays
ISIS.1	3.08	ISIS.6	4.20
ISIS.2	1.77	ISIS.7	3.57
ISIS.3	5.83	ISIS.9	3.77
ISIS.4	4.63	IPNS.D1	4.5
ISIS.5	9.85	IPNS.E1	2.52

Use of uranium nitride has been proposed for enriched targets [4]. There is, however, very little known about the behaviour of this material in high intensity proton beams. Also there are quite severe problems to overcome to get approval to use targets containing many critical masses of fissionable materials.

4 TARGET COOLING

The distribution of power deposited along a lead target for a 10 cm diameter beam is shown in figure 2.

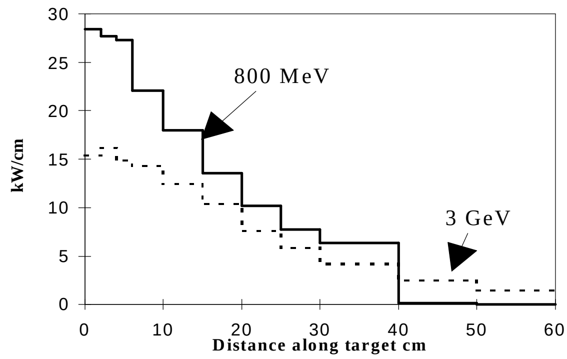

Figure 2. The power deposited along a lead target.

The limit to heat removal is the peak power density in the target and the maximum which can be handled in practical systems is about 4 MW/litre.

The majority of the heat is deposited by the incident proton beam and so for a given beam power the heat distribution in the target can be adjusted by changing the beam energy or current density. Figure 3 shows the peak power density in a Tungsten target as a function of proton energy [5] for a 7 cm diameter beam.

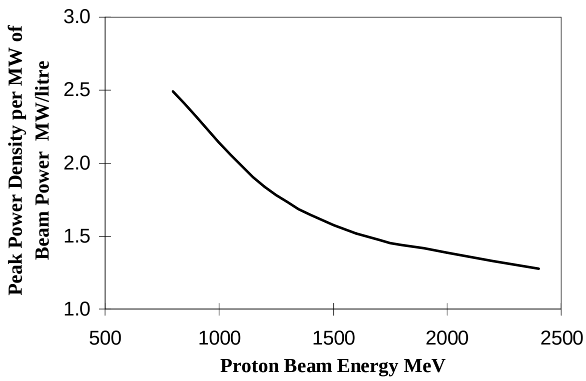

Figure 3. The variation of peak power density with proton beam energy.

Changing the current density can be accomplished by changing the beam size or profile. Figure 4 shows the variation of peak power density in a lead target for a variety of beam profiles and cross sections for a proton energy of 1334 MeV.

The quantity which gives a reliable measure of the heating problem is the current density in the beam. Above about 80 μAcm^{-2} the heat removal becomes problematic.

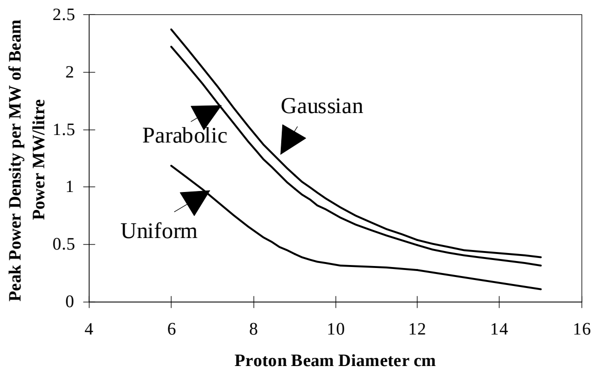

Figure 4. The variation of peak power deposited with beam profile and cross section.

Reducing the power density in the target by changing the beam characteristics will result in a larger target which in some applications is undesirable. There is a limit to the size of proton beams which can be considered practical as well as engineering constraints on the target size.

5 RADIATION DAMAGE

The damage to the target material and containers is generally manifested by embrittlement and has been reviewed in reference [6]. The consequences are a finite lifetime for the target. While a liquid metal target is a natural way of reducing the impact on the target itself, the damage to the target container still remains. As with heat removal, it is the density of interactions which is the crucial factor in determining the effects of radiation damage, so the effects can be reduced, for a given beam power, by increasing the proton beam size or energy. Again the proton current density is a very useful measure of the scale of the effects.

There is limited data available for irradiation effects on materials in a high intensity proton beam. The radiation field in a spallation target leads to much higher production of hydrogen and helium than typical of a reactor. This, and high transmutation rates, makes extrapolation from reactor data very uncertain.

An extensive experiment to measure radiation damage effects in most materials of interest to spallation sources will take place at LAMPF, starting this yea, as part of the Accelerator Production of Tritium (APT) project at Los Alamos [10].

The first ISIS target, irradiated for 60 MWdays, will be dismantled for detailed analysis at KFA Jülich this year. The peak temperature of this target doubled during operation due to the effects of irradiation.

There is considerable scope for development of new alloys suitable for spallation targets and this is the most likely area for improvement in performance in the future.

6 CONTINUOUS AND PULSED SOURCES

6.1 Fast pulse sources

A particular problem exists for targets on pulsed sources. When the duration of the pulse is short the heat is deposited faster than it can be conducted away. The resulting fast temperature rise in a solid target produces high transient thermal stress waves (sometime known as thermal shock). Typically, this will be an important consideration for pulse lengths less than a few microseconds. This effect is also a problem in liquid metal targets where the liquid transmits pressure waves to the target container resulting in high stresses. This is a major concern for the ESS mercury target [7]. Transient thermal stresses may well be the ultimate limit for the power of fast pulsed sources.

A fast pulsed spallation source to provide thermal neutron beams for condensed matter research uses small, typically 0.5 - 1 litre hydrogenous moderators to slow down the fast neutrons from the target. They are sized to maintain short pulses (10 - 150 μs fwhm) and the designs incorporate neutron absorbers to eliminate neutrons moderated by coolant and the reflectors. In this case thermal neutron absorption in the target material is a positive advantage. These systems also require the target to be as compact as possible to maintain high neutron fluxes feeding the small moderators. Increasing the target size leads to a reduction on the neutron beam fluxes.

6.2 Continuous and quasi-continuous source.

For continuous and quasi-continuous spallation sources (pulse lengths ~200 μs or greater) the heat loading does not lead to the potentially high transient thermal stresses of the fast pulse targets. The total number of neutrons produced becomes a crucial quantity and minimum neutron absorption is then vital. This can be achieved by optimisation of the geometry and choice of target material.

For these sources a more extended target generally has less of a penalty in neutron flux than in the case of fast pulsed sources. The consideration of neutron economy is very similar to that in reactor design.

7 SOLID WATER COOLED TARGETS

7.1 Solid targets

All currently operating spallation sources use solid water cooled targets. The TRIUMF facility has a water cooled lead target/beam stop in which the lead melts in the beam region. Low power targets such as KENS and MLNSC at Los Alamos use solid blocks with edge cooling. This technique can be extended to a beam power of about 300 kW as in the AUSTRON study [8] but is inadequate for much higher power beams. Several designs have been developed which segment the target material into plates, rods or spheres. Examples are described below.

7.2 Plate targets

A schematic diagram of the ISIS target is shown in figure 5. This is typical of plate targets. A stack of plates containing a disc of target material (either tantalum or depleted uranium) is cooled by pressurised water flowing in the 1.75 mm wide gaps between them. The complicated flow arrangement of this target has been designed specifically to give sufficient sensitivity that flow and pressure drop monitoring can detect small <0.2mm) reduction in the cooling gaps as the target material swells. Also this target has an independent water circuit which cools the edges of the plates. This has sufficient capacity to remove the heat from radioactive decay after proton beam turn off

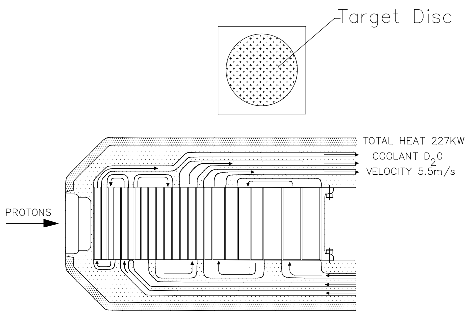

Figure 5. A schematic view of the ISIS target.

A design for a tantalum plate target has been developed for the 5 MW beam of the European Spallation Source study. The principal difference between this and the ISIS target is the thickness of the plates.

7.3 Rod targets

Rod bundles have been used in many reactor designs and this concept has been adopted for the initial target at the SINQ [9] source at PSI.

This is a continuous source and so a low neutron absorption cross section in the target is crucial. The target material chosen is Zircaloy where the low absorption more than compensates for its relatively low atomic mass compared to tantalum or tungsten both of which have substantial absorption cross sections. The target will be developed to use rods made from aluminium tubes filled with lead. Finally a liquid lead, or lead/bismuth target will be used.

Rods are also proposed for the target design of the APT project at Los Alamos [10]. This envisages a 150 MW proton beam at 1.3 GeV which gives 95 MW of heat in the target. To give acceptable power density in the target the proton beam cross section will be 160 cm high by 16 cm wide. This is equivalent to a proton current density of 45 μAcm^{-2} which is about the same as the current density in the existing LAMPF beam stop. So despite the enormous beam power proposed the target does not demand new technology.

The target will be constructed from bundles of tungsten rods about 3 mm in diameter 22 cm long, each tube containing typically 100 rods. Tubes are stacked to give target layers 180 cm high, 25 cm wide and 4 cm thick with a gap between layers. Neutrons produced in the tungsten then escape via these gaps. This design reduces the path length of neutrons in the target material which compensates for the relatively high neutron absorption in tungsten.

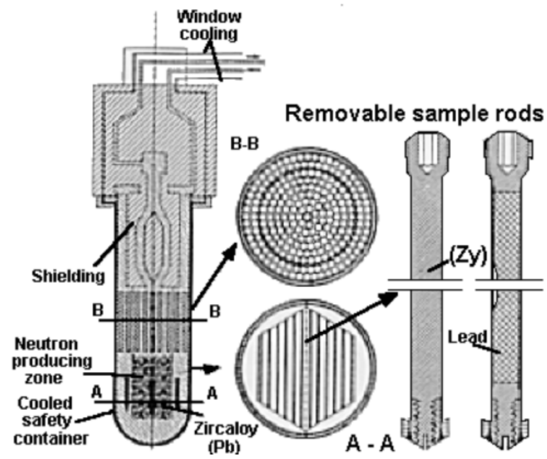

Figure 6. The SINQ target concepts

An alternative to be used for the MLNSC upgrade target and the proposed LPSS [11] source is to have tungsten rods enclosed in helium filled Inconel 718 tubes. The design only relies on radial conduction and so is tolerant of brittle fracture of the tungsten.

7.4 Rotating targets

An alternative way of reducing the power density in the target is to use a rotating wheel. The wheel diameter is typically 1 - 2 m with the proton beam incident on the rim. The speed of rotation is chosen such that an element of the target is fully cooled during one revolution. This concept was studied extensively in the SNQ project [12] and while it has the potential for very high beam powers the target systems are mechanically very complex. The engineering of the rotating seals for the services and the design of the remote handling required are both demanding engineering challenges.

8 LIQUID METAL TARGETS

Liquid metal targets have several advantages. The mean density of the target is not diluted by coolant. They do not suffer from radiation damage so should last the lifetime of a facility, thus easing the waste disposal problem. There is extensive experience with liquid metal circuits in the reactor industry.

However their use in spallation sources is not without difficulty. Containment in the event of pressure vessel failure is more difficult than for a solid. Lead and lead/bismuth both increase in volume on solidification so a heating system to keep them liquid is essential. Corrosion of the container can take place.

Uncertainty in the effects of radiation damage and transient thermal stress on solid targets has resulted in a mercury target being chosen for both the ESS and Oak Ridge spallation source [13] studies. Mercury has the advantage that no heating system is required to keep it liquid and the thermal neutron absorption is an advantage. The ESS design is illustrated in figure 7.

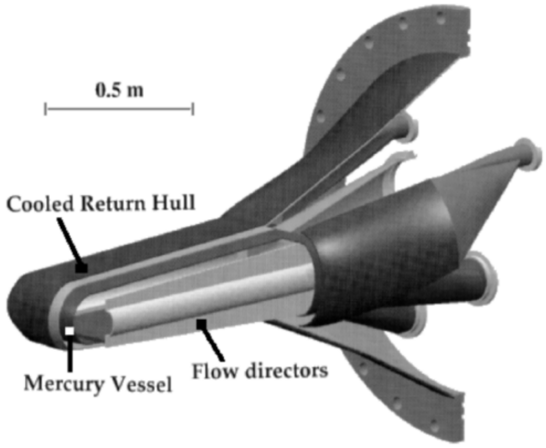

Figure 7. The ESS mercury target.

The ESS is a fast pulsed source with a 5 MW 1.334 GeV proton beam. Early analysis indicates that the pressure waves from the proton pulses result in unacceptable stresses on the container. The current design envisages a system to introduce small bubbles of helium into the mercury to provide compressibility to the target medium and so damp the pressure waves.

This is an illustration that when designed in detail the liquid metal target systems are generally more complex than those of a solid water cooled target. This has to be judged against potentially more reliable operation and in many cases higher neutron fluxes.

7 FUTURE PROSPECTS

The success of the operational sources has shown that high power spallation sources, ~1 MW or greater, have the potential to replace reactors in many applications.

Sufficient success has been achieved in the design studies to give confidence that practical solutions exist for the technical problems associated with the design of target systems. The debate between the relative merits of the basic concepts - solid water cooled, both stationary and rotating, and liquid metal targets, will continue. Novel designs will undoubtedly be developed.

The key question is the behaviour of materials under intense proton bombardment. The fusion programme has had marked success in developing new alloys and there is a clear need for a similar effort to underpin the design of high power spallation targets.

There is every reason to be optimistic about the future. The SINQ source will operate in the near future and there is a good prospect of approval being given for construction of new facilities in the USA. It is to be hoped that these will provide the operating experience which is crucial for the design of future high power spallation targets.

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