THE POTENTIAL OF FLUIDISED POWDER TARGET TECHNOLOGY IN HIGH POWER ACCELERATOR FACILITIES

C.J.Densham, O.Caretta, P.Loveridge, STFC Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK
T.W.Davies, University of Exeter, UK
R.Woods, Gericke Ltd, Ashton-under-Lyne, OL6 7DJ, UK

Abstract

This paper describes the potential of fluidised powdered material for use as a particle production target in high power particle accelerator based facilities. In such facilities a multi-MW proton beam is required to interact with a dense target material in order to produce sub-atomic particles, e.g. neutrons for a neutron source or pions for a so-called conventional neutrino beam, a neutrino factory or a muon collider. Experience indicates that thermal transport, shock wave and radiation damage will limit the efficiency and reliability of facilities utilising solid targets at around 1 MW beam power. Consequently liquid mercury has been adopted as the target technology for the latest neutron facilities SNS and J-SNS at ORNL and Tokai respectively, and is the baseline for a neutrino factory and muon collider. However mercury introduces new difficulties such as Cavitation Damage Erosion. This paper discusses how a fluidised powder target may combine many of the advantages of a liquid metal with those of a solid, and describes an experimental programme at RAL that is currently underway to implement this technology.

BACKGROUND: TARGET TECHNOLOGY PROGRESSION

The majority of accelerator based facilities that require the interaction of a particle beam with a target have hitherto utilised a solid material for reasons of physics performance and engineering convenience. As pulsed energy densities and integrated powers have increased, peripherally cooled static monolithic targets have given way to subdivided, directly cooled targets with a consequent increase in heating and activation of cooling water, or to rotating or radiatively cooled targets. Solid target lifetimes are limited by radiation damage, in combination with thermal transients and shock-wave damage resulting from pulsed beams.

A new generation of accelerator facilities requires target systems to dissipate powers in the MW region, with pulsed energy deposition of 100s of J/g and beyond. It is widely expected that difficulties of radiation damage, shock wave damage, thermal transport and of avoiding unacceptable compromises to physics performance will preclude the use of solid targets in such facilities. Consequently liquid metal, namely mercury, has been adopted as the target technology for the latest neutron facilities SNS and J-SNS [1] at ORNL and Tokai respectively, and is the baseline for a neutrino factory and muon collider [2].

Liquid metal targets have been used successfully for short term operation in pulsed mode at ISOLDE at CERN [3]. They can offer advantages compared with solids in terms of physics performance i.e. material density, and with power dissipation and radiation damage tolerance. Fully dense target material can be circulated so that it can be externally cooled and radioactive products removed. However, problems arise with shock waves generated in contained liquid metal targets by pulsed beams. Cavitation Damage Erosion to the target window material is caused by the generation and collapse of tiny vapour bubbles that result when a compressive shock wave is reflected as a tensile wave at the container wall [4]. In principle this may be solved by the injection of helium bubbles into the liquid metal, or by the creation of a gas wall. Successful development of such a system is expected to be required to achieve the c.1 MW design powers of the SNS and J-SNS facilities. The problem of shock waves on container walls is planned to be avoided in the baseline target system for a neutrino factory by the use of an open liquid mercury jet injected into the pion capture solenoid at a velocity of 20 m/s to generate sufficient interaction length with the incident proton beam. Such issues were studied in the MERIT experiment carried out at CERN in 2007 [5], which demonstrated that the solenoidal field damped the pulsed beam induced mercury splashes, as predicted by magnetohydrodynamic simulations [6]. However, arguably crucial issues remain, for example (i) the proposed combined mercury jet capture and beam dump which must be able to handle both the entry of the mercury jet and the non-disrupted beam in the event of a beam mis-steer. Other potential problems include (ii) interaction of remnant high velocity droplets of liquid metal with the vessel walls, (iii) Liquid Metal Embrittlement, a known phenomenon in the field of liquid metal handling, and (iv) radiochemistry where the generation of many chemical contaminants in the liquid metal may lead to as-yet unknown corrosion processes in the container walls.

A neutrino factory poses many technological challenges in addition to those related to the target station and the earliest schedule foreseen for contruction is around 2020. However for a neutrino Superbeam, a so-called conventional neutrino beam operating at beam powers of over 1 MW, the target is the single biggest technological hurdle to be overcome. The T2K experiment will push the limits of what can be achieved with a monolithic graphite target [7], with a phase 1 design beam power of 750 kW. As yet there is no target design for the T2K roadmap which foresees a rise to 1.66 MW by 2014. A helium cooled static packed bed is the obvious next target technology, however from experience gained at existing facilities, no static target seems likely to have a useful lifetime for the ambition of a 3-4 MW Superbeam to be realised. A free liquid metal jet within a magnetic horn is not viable since, unlike for a solenoid, there is no magnetic field within the bore of a horn to damp out the high velocity jets generated by the pulsed proton beam. Corrosion of the aluminium material would also be a severe problem. A moving and recirculating solid target system would be difficult to engineer in a reliable way for any facility where the target has to be installed within either a magnetic horn for a SuperBeam or a high field solenoid for a Neutrino Factory/Muon Collider.

THE FLOWING POWDER TARGET

With regard to international aspirations for neutrino experiments, it seems likely that within five years a multi-MW neutrino Superbeam will provide the first serious challenge in target technology for neutrino experiments, followed some time later by a Neutrino Factory and after that by a Muon Collider. A future generation of short-pulse neutron facilities reaching multi-MW beam powers may also require a new target technology.

It is in this context that a research programme has been initiated at the Rutherford Appleton Laboratory in the UK to explore the potential of flowing, fluidised powder targets [8]. To date, the research has studied a configuration similar to the baseline for the neutrino factory, namely an open jet, for reasons of direct comparison. It is intended to extend this to the study of contained flowing powder for possible application to a SuperBeam or neutron production target. Numerical simulations are not generally useful in the study of the behaviour of bulk powders, and so the research programme is predominantly experimental.

The motivation for studying a flowing powder target is to investigate whether such a technology can combine some of the advantages of a solid target with those of a liquid while avoiding some of the disadvantages of either.

The attractions of a static granular target have been outlined before. A helium cooled granular target was investigated for a neutrino factory [9], however the static design had inherent cooling limits. A free-falling powder target has been subject to preliminary investigation [10] however was not considered worth further study.

The attractions foreseen for a flowing powder jet target include:

- Intrinsic resilience of individual grains to beam induced shock wave damage compared with macroscopic solid targets. In essence, a powdered material is already broken and can only either be subdivided into ever smaller grains or sintered into clumps. Pulsed heating of a roughly spherical shape leads to an initial hydrostatic stress field and zero initial resultant stress. Stress waves can build up if the characteristic time constant for the stress wave to traverse the particle (c. 100 ns for 250 μm grains) is significantly larger than the beam pulse width, ~ ns for a neutrino factory or ~ μs for a SuperBeam. It can be shown that the smaller the particle size, the smaller will be the magnitude of the resultant stress waves that develop, for a given beam pulse width.
- Pulsed beam induced stress waves are contained within each separate grain of material, and cannot generate splashing or jets in the bulk powder as can occur with liquid metals. Since the carrier gas is compressible, the only coupling that can occur is between touching grains and between the powder and pipe wall. It is contended here that this will be an insignificant effect since surface velocities of a shocked solid [11] are very low compared with those of a liquid [6]. For example, sand-bags are commonly used to absorb impacts from bullets.
- The heat conduction path is very short in a powdered material compared with a solid. While there are difficulties in removing high power densities from a static powder using gas flow alone [9], a flowing powder has excellent heat transfer characteristics both within the powder material itself and with container walls. This is the mechanism used in heat exchangers for powder handling, and raises the possibility that a flowing powder may be able to remove heat loads generated by secondary particle interactions with pipe walls. The effectiveness of this could be investigated experimentally off-line.
- As for a liquid, a flowing powder can be pumped away from the interaction region and cooled externally using heat exchangers. This offers the potential for powders to be able to withstand both high power densities and high integrated powers within the beam interaction region.
- The above factors raise the possibility of a flowing refractory metal powder (melting point ~3000°C) being able to withstand multiple beam pulses (ΔT ~100°C) interacting with the same material before cooling.
- No cavitation can occur in a powdered solid material within a carrier gas, since this is a phenomenon associated with liquids only.

- A powdered material does not suffer the same problems of geometrical changes that can occur due to radiation damage of solid targets. The material is continuously reformed as for a liquid target.
- Eddy current generation and consequent interaction forces of a conducting powder with a solenoid have been studied using the Vector Fields code. The retarding force on a powder grain was shown to reduce as a function of radius to the power of 5, giving a negligible effect for the grain size <250 μm used in experiments thus far.
- Fluidised beds and powder jets are a mature technology developed for the conveyance of powders in the chemical, material and food processing industries. Consequently, it is possible to draw on such experience with the design of various components in the development of a complete target system. For example, both gravity fed and screw-driven heat exchangers have been developed to cool powders, and nozzles designed for use with vacuum pumps to lift powder in 'lean phase', i.e. low powder density, from a material hopper. Solutions exist for many erosion problems e.g. at pipe elbows.
- Most of the questions relating to the implementation of a flowing powder target can be investigated experimentally and, crucially, off-line. Also, unlike mercury, powdered tungsten is non toxic. These factors mean that a productive experimental programme can be undertaken at a relatively modest cost.

IMPLEMENTATION OF A FLOWING POWDER TARGET

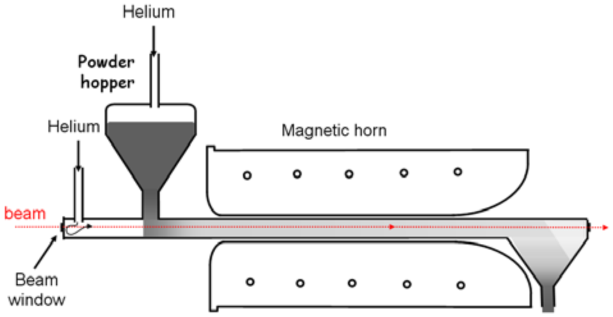

Figure 1. Schematic layout of flowing powder Superbeam target.

Potential applications of flowing powder targets include:

- A neutrino superbeam, e.g. for a T2K upgrade or based on the proposed SPL at CERN. A flowing powder could be conveyed in a pipe through a magnetic horn. An outline schematic of such a system is shown in Figure 1. An intermediate tube could be introduced to provide a path for coaxial gas return from an air lift system (see below).
- Neutrino factory. An open jet of tungsten powder could replace the baseline mercury jet, as illustrated in Figure 2. Alternatively, the powder could be conveyed in a closed pipe if sufficient cooling of the pipe can be achieved. Consequently the velocity of the jet can be governed purely by thermal and geometrical issues of interaction with the proton driver beam.
- Spallation Neutron Target. A high Z material, ideally depleted uranium powder for maximum neutron production, could be conveyed through a pipe.
- Radioactive Ion Beam production by projectile fragmentation of an open jet.
- High power density and high integrated power beam dumps for a variety of applications, e.g. neutrino factory, superbeam or linear collider.

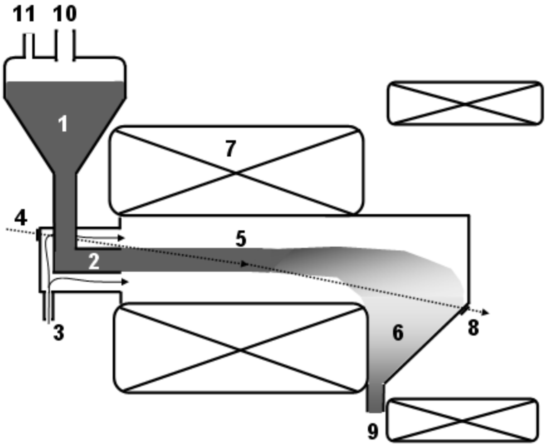

Figure 2. Open powder jet illustration for a neutrino factory target, with (1) pressurised powder hopper, (2) discharge nozzle, (3) recirculating helium to form coaxial flow around jet, (4) proton beam entry window, (5) open jet interaction region, (6) receiver, (7) pion capture solenoid, (8) beam exit window, (9) powder exit for recirculation, (10) return line for powder to hopper, (11) driver gas line

Figure 3 shows a schematic outline of a circuit that would provide continuous operation and recirculation via an external heat exchanger.

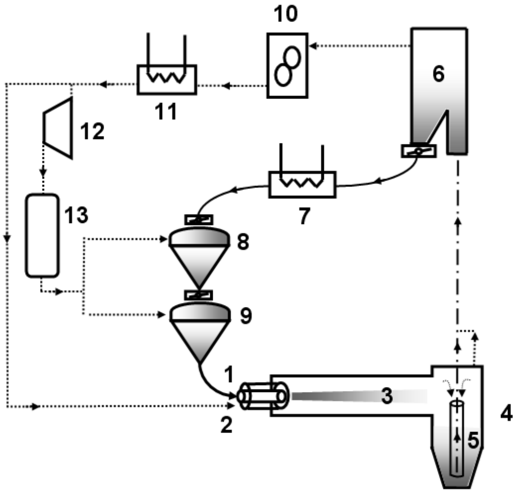

Figure 3 Schematic outline of a circuit for continuous powder target supply, with (1) powder discharge nozzle, (2) gas return line forming coaxial flow, (3) target jet, (4) receiver hopper, (5) suction nozzle for gas lift, (6) gas lift receiver vessel with filter, (7) powder heat exchanger, (8) and (9) pressurised powder hoppers, (10) Roots blower, (11) gas heat exchanger, (12) compressor, and (13) gas reservoir.

LIMITATIONS AND CHALLENGES FOR POWDER TARGET TECHNOLOGY

Flowing powder target technology naturally poses new difficulties and limitations that do not exist for either solids or liquids. Many of these require experimental investigation:

- Erosion is almost certainly the key technical issue, for example at pipe bends, nozzles, valves and in receiver vessels/hoppers. This is a particular problem if the powder is re-circulated at high velocity in a lean phase. The powder handling industry has developed methods of mitigating the abrasion problem, for example with the use of re-circulating pockets to reduce the velocity at the outside of bends, and with the use of hardened materials. Good circuit design to minimise this problem is vital. It is possible to avoid lean phase flow and to recirculate using dense phase flow only, however this would require more valves and a more complex circuit. Design for regular replacement of the entire circuit will almost certainly be necessary.
- Achieving sufficient, uniform and reliable material density is a key issue in terms of particle production efficiency. A typical material packing fraction for a powdered material is 50% and consequently this sets an upper bound for a flowing powder target. In order for a flowing powder to become a serious contender for a facility, this limitation would need to be offset by other advantages, for example by increased reliability, by permitting use of an element of greater density than would otherwise be possible, or by being able to withstand higher integrated or pulsed beam powers.
- For an open powder jet, high velocities are typically required to generate sufficient interaction length. This regime has been found to generate velocity gradients ranging from around 7 m/s at the bottom of the jet rising to 15 m/s at the top. This causes variable density and a divergence of the jet. It also requires higher gas pressures (around 4 bar for the above test) increasing the risk of erosion.
- For a contained flowing powder target, there remain issues relating to secondary particle interactions with a pipe wall. These include heat transfer, shock wave damage and radiation damage all of which will be most significant for high Z targets. If cooling by the flowing powder or by re-circulating helium flow is insufficient then it may be necessary cool the pipe by a water spray, the technique used to cool the inner conductor of magnetic horns.
- It is possible that rapid expansion of the carrier gas could cause damage to the wall of a contained powder or deterioration of an open jet. The mechanism would be heat transfer from the powder to the gas since direct beam heating of the carrier gas is negligible. Such a mechanism could be tested with a few proton beam pulses impinging a thimble of powder in a helium atmosphere. The result would be directly comparable with a similar experiment carried out for a thimble of mercury [12].
- Another technical difficulty will be that of incorporating beam windows to separate the driver gas from the accelerator vacuum upstream and decay volume or muon front end downstream. The requirements are similar to those for a mercury jet target and so there is direct synergy between the mercury and powder technologies. Beam windows would have to be separated from the target material itself to minimise the risk of erosion damage. It would be desirable to arrange the proton beam entry window to be far upstream of the target and for a large beta function beam to reduce the power density deposited in the window material.
- Interactions with a solenoidal magnetic field could cause charged powder grains to be focussed along the bore of the solenoid causing damage to a downstream window.
- Activated powder would need careful remote handling, however radiological and safety issues are not expected to be any more severe than for mercury, and could be more benign. Contaminated powder can be removed from pipe walls by circulating a clean

powder material. A powder disposal plant could be incorporated into the facility e.g. by vitrification, a method commonly used in the nuclear industry.

STATUS OF EXPERIMENTAL PROGRAMME

A test rig has been commissioned at RAL to study off-line as many of the issues highlighted above as possible. The rig has been used to generate flowing powder in a dense phase, driven through a pipe by gas pressure. Tungsten powder has been used as a prototype high-Z refractory metal target. Both air and helium have been used successfully as the driver gas; helium would be used in an on-line facility for its favourable heat transfer properties and to minimise effects of gas activation and ionisation.

The powdered material is loaded at maximum density into the pipe and driven along it by gas pressure as a 2-phase fluid. The flowing powder exits the pipe as an open jet which lands in a receiver vessel. The tungsten powder is then re-circulated using a gas lift from the receiver vessel. Figure 4 shows a photograph of the test rig.

Figure 4. Powder handling test rig at RAL.

An automated control system with a graphical user interface was written to operate the rig through the following stages and to log all instrumentation data. Operating in batches of c.100 kg, the tungsten powder is conveyed from a pressurised hopper through a horizontal 1 m long pipe with a 20 mm diameter bore, opening into a 200 mm diameter transparent tube to simulate entry of the jet into a pion capture solenoid. Air is drawn through this by means of a 30 kW roots blower drawing a vacuum of 600 mbar (abs) on the receiver hopper. A coaxial flow of air around the jet is achieved by introducing an annular return from the blower at entry of the discharge pipe into the transparent tube. The powder is lifted from the receiver hopper with a specially designed nozzle which uses coaxial air flow to fluidise then lift the powder to a high level receiver vessel connected to the roots blower via a filter. Two sliding valves open to drop the powder into the pressure hopper which is then ready to be pressurised for the next batch. Automatic control of the circuit is achieved using a combination of timed processes and feedback from sensors e.g. a load cell to measure the mass of powder in the pressure hopper.

The jet was filmed using a Vision Research PHANTOM 7.1 high speed video camera from the EPSRC Instrument Loan Pool. This was set to 5000 frames per second, enabling estimates of the jet velocity to be obtained. During March 2009 a total of 31 cycles conveyed 3000 kg powder in the study of the effects of varying flow geometry, conveying pressure over the range 2 – 5 bar and coaxial flow velocity over the range 10 – 30 m/s.

A driving pressure of 2.0 bar generated a uniform jet velocity of 3.7 m/s and a mass flow rate of 7.9 kg/s. From this it was possible to estimate a jet density of 42% ±5%. This is close to the maximum achievable value of around 50%. Figure 5 shows a still image from the high speed camera.

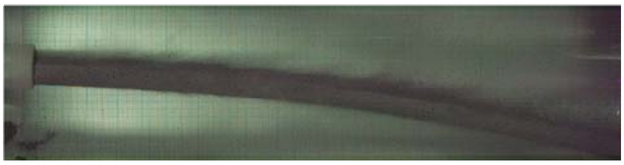

Figure 5. Tungsten powder jet of c.42% material density

SUMMARY

It has been demonstrated that tungsten powder can be readily fluidised within a pipe in dense phase and can form a dense, stable and coherent jet. Both these configurations have the potential to form the basis of a multi-MW target for future accelerator based facilities. An experimental programme is underway to explore the implementation and limits of such a system.

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