A Flowing Granular Tungsten Pion Production Target for a Muon Collider at CERN

Abstract
The potential of pneumatically fluidized and flowing granular tungsten as a high-Z target technology for intense pulsed power accelerator applications such as a future muon collider (MC) at CERN is introduced. A muon collider has a combination of requirements that are well beyond the limit of any existing target technology. A high-Z target is required to be suspended within the bore of a high field solenoid and subject to the high pulsed power density of a multi-MW proton beam. Flowing granular tungsten pneumatically conveyed within a pipe is proposed as an alternative to the current baseline technology proposal of an open mercury jet. The status of off-line and on-line experimental research into such a technology is described, followed by an outline of a future program of work required to fully demonstrate its suitability for a muon collider or other facility with similarly demanding requirements.

Authors
C.J. Densham*, P. Loveridge, D. Wilcox, T.R. Davenne, J. O'Dell, C. Rogers (STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire, UK)

J.J. Back (University of Warwick, Coventry, UK)

N. Charitonidis, I. Efthymiopoulos (CERN, Geneva, Switzerland)

D. Sprouster (BNL, US)

Muon Collider Collaboration

*chris.densham@stfc.ac.uk

(Dated: August 31st, 2020)

1. Introduction

The 2020 Update of the European Strategy for Particle Physics [1] recommended that muon beam R&D should be considered a high priority future initiative. This led to the formation of a muon collider collaboration which adopted the conceptual design facility outline developed by the US DoE funded Muon Accelerator Program (MAP) [2] as a baseline for a muon collider (MC) at CERN. One particularly challenging element of this design is the proposed target. An open liquid mercury jet and 4 MW proton beam was the MC baseline for many years although the conventional neutrino beam standard of a solid graphite target was also suggested for 1 MW operation [3]. The demands on any target material for a MC at MW operation are extreme as it must withstand very high pulsed power densities, cyclic thermal stresses/pressures and radiation damage, must efficiently remove the deposited heat, and be optimized for secondary particle production. Even if the technological challenges e.g. consequences of splashing [4] can be overcome, the radiological and toxicity issues make it unlikely that an open mercury jet could be adopted at CERN. For example, the European Spallation Source (ESS) project [5] concluded that the license application process for a *contained* liquid mercury target in Europe, as is currently employed at ORNL/SNS and JPARC/J-SNS, would be prohibitively expensive and time consuming with no guarantee of success [6]. The small spot size and high instantaneous beam intensity would make any fixed graphite target challenging, especially if several MW proton beam powers are required. A rotating solid tungsten wheel as adopted for the ESS is not suitable for a muon collider due to the high deposited energy from the intense pulsed beam. Nor can it be integrated within either a capture solenoid (the baseline) or a magnetic horn (a more conventional but less efficient alternative), since the wheel will need to be placed inside a gap which will lead to unacceptably high radiation shine as well as a dip in the peak focusing magnetic field strength. As an alternative, the High Power Targets Group at RAL has developed a fluidised tungsten powder target technology which combines some of the advantages of a liquid metal with those of a solid. The granular material flowing within a pipe is expected to be able to withstand extremely intense pulsed beam powers without the cracking or radiation damage limitations of solid targets, and without the cavitation issues associated with liquid targets [7]. Moreover, its disruption speed inside a gaseous helium atmosphere has been measured to be of the order of a few m/s [8]. However, a fluidised powder target introduces new challenges, such as achieving reliable circulation and continuous stable horizontal dense phase flow, managing heat dissipation, mitigating radiation damage and erosion of the containing pipework and beam windows, as well as ensuring reliable diagnostics and controls for the powder handling processes.

2. Previous work

Tungsten's high density (19.6 g/cm3) is beneficial for particle production and as a refractory metal is well suited as a target material for a muon collider. However it is considerably denser than the materials which are typically pneumatically conveyed and lies well beyond current technology. An offline test rig was built at the Rutherford Appleton Laboratory (RAL) in order to demonstrate the feasibility of pneumatic fluidisation and conveyance of powdered tungsten [9, 10]. The rig can fluidize and lift sub-250 micron powder using suction and eject it in solid dense phase as a coherent open jet or contained pipe flow with a bulk fraction of c.50%.

Air was used for the test rig but helium is proposed for actual target applications due to its favourable heat transfer properties and to minimise radiological issues. We propose contained flow as being most suitable for use as a particle production target [11]. Subsequent developments have enabled the rig to continuously recirculate the powder, providing an uninterrupted stream of target material.

The response of a static open trough of tungsten powder to a high energy proton beam was investigated in 2012 and 2015 at the HiRadMat facility at CERN [12]. Eruption velocities from the free surface, due to the ionisation of the grains by the proton beam, were much lower than for liquid mercury subjected to the same energy density [13,14,15], although for the latter this effect was significantly reduced by the capture solenoid magnetic field. It is anticipated that the beam-induced disruption should be considerably lower for a powder contained inside a tube although this would need to be demonstrated in a future HiRadMat experiment. Overall, we expect a contained powder target system to be considerably less damaging to its surroundings than an open liquid mercury jet and also less problematic from a radiological point of view.

3. Future Plans

The fluidised tungsten powder concept shows promise as a target for a MC or e.g. future high-intensity CLFV experiments [16], but further development will be required to demonstrate its suitability for use in an operating facility. Fortunately, the vast majority of the technical challenges can be tackled by relatively inexpensive R&D, such as developing the offline test rig at RAL. This currently operates entirely by timed “batch” processes involving a number of pneumatically operated sliding gate valves. An operating facility would ideally eliminate such moving parts. Careful selection of the pipework and beam window material will be required (e.g. SiC-SiC composite). Bespoke designs for high-erosion regions such as bends may be required, and long-term erosion measurements essential to demonstrate that the required target lifetimes of months or years can be achieved. Measurements of the heat transfer between the flowing tungsten powder and the surrounding containment tube would also be desirable. Commercial powder heat exchangers are readily available, although these may need to be adapted for use with tungsten powder. A future on-line experiment at HiRadMat is intended to investigate the effect of an intense pulsed proton beam on tungsten powder contained within a tube, using laser doppler velocimetry to measure any stresses transmitted from the granular material to the pipe wall. In addition to this practical work, an engineering feasibility study will investigate how to integrate the complete tungsten powder system within a capture solenoid for a muon collider target station. This will require input from a comprehensive physics design study, which will use simulation codes to calculate the predicted particle production rates and deposited energy densities in order to select the best geometry layout and beam parameters that will optimize the performance of the muon collider within the expected engineering constraints.

Alongside this work, a detailed post-irradiation examination of the powder with X-ray diffraction studies will quantify the radiation damage from the future HiRadMat experiment and give further insights into structural damage that the proton beam can cause in granular materials. Possible cross-section measurements of the powder hadron production may be pursued in collaboration with specialized facilities in the CERN North Area, which can then be used to improve the physics simulation predictions for optimizing the performance of the MC.

Bibliography

[1]http://cds.cern.ch/record/2721370/files/CERN-ESU-015-2020%20Update%20European%20Strategy.pdf
[2] S. Geer, M. Zisman et al, “R&D PROPOSAL FOR THE NATIONAL MUON ACCELERATOR PROGRAM” Revision 5bb; February 24, 2010 (FERMILAB-TM-2459-APC)
[3] https://lss.fnal.gov/archive/2010/conf/fermilab-conf-10-251-apc.pdf
[4] X. Ding et al., Carbon and mercury target systems for muon colliders and neutrino factories, IPAC16 (2016).
[5] R. Garoby et al, “The European Spallation Source Design”, Physica Scripta, Volume 93, Number 1 (2017)
[6] R. Moormann et al, “Safety and Licensing of the European Spallation Source (ESS)” http://juser.fz-juelich.de/record/41676 (2004)
[7] B.Riemer et al, “Cavitation damage experiments for mercury spallation targets at the LANSCE–WNR in 2005”, Journal of Nuclear Materials, Volume 377 Issue 1, 30 June 2008, Pages 162-173 https://doi.org/10.1016/j.jnucmat.2008.02.028
[8] N. Charitonidis (PhD Thesis) https://cds.cern.ch/record/1711801/files/CERN-THESIS-2014-067.pdf
[9] O. Caretta, C. J. Densham, T. W. Davies and R. Woods, “Preliminary Experiments on a Fluidised Powder Target,” in Proceedings of EPAC08, WEPP161, Genoa, Italy, 2008.
[10] C. J. Densham, O. Caretta and P. Loveridge, “The potential of fluidised powder target technology in high power accelerator facilities,” in Proceedings of PAC09, WE1GRC04, Vancouver, BC, Canada, 2009.
[11] T. Davies, O. Caretta, C. Densham and R. Woods, “The production and anatomy of a tungsten powder jet,” Powder Technology, vol. 201, no. 3, pp. 296-300, 2010.
[12] I. Efthymiopoulos et al., “HiRadMat: a new irradiation facility for material testing at CERN”, Proceedings of IPAC2011, San Sebastián, Spain TUPS058
[13] O. Caretta, T. Davenne et al., “Response of a tungsten powder target to an incident high energy proton beam,” Physical review special topics - accelerators and beams, vol. 17, no. 10, DOI: 10.1103/PhysRevSTAB.17.101005, 2014.
[14] O.Caretta, P.Loveridge et al., “Proton beam induced dynamics of tungsten granules,” Physical Review Accelerators and Beams, vol. 21, no. 3, DOI: 10.1103/PhysRevAccelBeams.21.033401, 2018.
[15] T. Davenne, P. Loveridge et al., “Observed proton beam induced disruption of a tungsten powder sample at CERN,” Physical Review Accelerators and Beams, vol. 21, no. 7, DOI: 10.1103/PhysRevAccelBeams.21.073002, 2018.
[16] M. Aoki, R.H. Bernstein et al, “A New Charged Lepton Flavor Violation Program at Fermilab (ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms)”, LoI submission to Snowmass (August 2020).