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# Update on MOMENT's Target Station Studies

**N. Vassilopoulos**∗†
*Institute of High Energy Physics, CAS, Beijing 100049, China*
*E-mail:* vassilopoulos@ihep.ac.cn

**Han-Jie Cai**
*Institute of Modern Physics, CAS, Lanzhou 730000, China*
*E-mail:* caihj@impcas.ac.cn

The muon decay medium-baseline facility (MOMENT) is a high intensity neutrino beam proposed in China, aiming to measure leptonic CP-violation. The primary proton beam has 15 MW of power provided from an ADS type of linac, which poses a radiation challenge to a capture system that consists of an adiabatic superconductive solenoid from 14 T to 3 T, and a high power liquid or fluidized target located inside the main capture coil in order to maximize the pions capture and reduce their transverse momentum. Though the initial baseline is the liquid Hg-jet, a novel fluidized waterfall-like granular target is also being studied. In this paper, we present updated studies for the compact waterfall granular target concerning simulations done with discrete element method and particle physics Monte Carlo analyses. Our continuous aim is to calculate the optimal physical parameters of the waterfall in order to comply with the physics (captured meson and muon yields) requirements of MOMENT and to remove the heat efficiently.

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∗Speaker.

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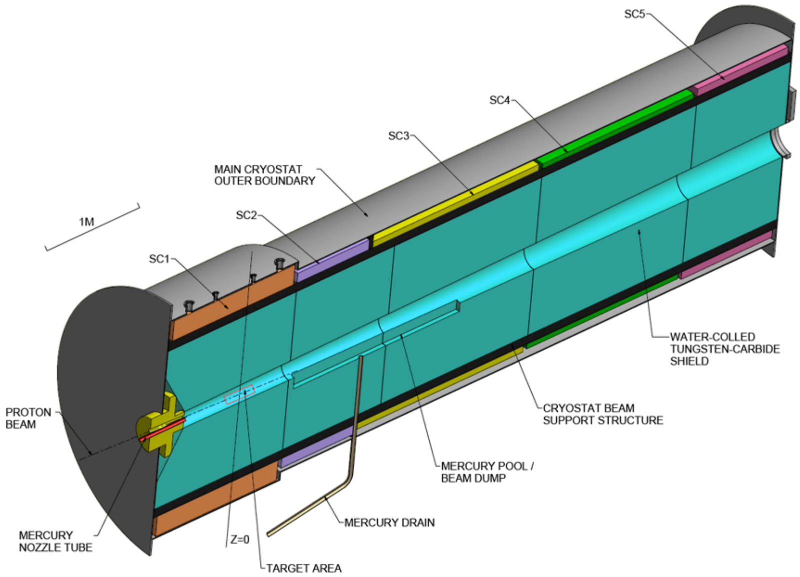


**Figure 1:** Schematic representation of the capture solenoid and its elements. The first two coils are foreseen with $Nb_3Sn$ and the following three with NbTi superconductor wires.

## 1. Description

The capture system of MOMENT is proposed to have a superconducting capture solenoid with five coils and a liquid Hg-jet target [1]. In summary, the solenoid baseline option has a strong adiabatic field from 14 T to 3 T along 5 m in order to maximize the charged pion capture. This can be achieved with 5 high aperture coils, the first two made by $Nb_3Sn$ and the following three by NbTi superconductor wires. The shielding is foreseen to be made by tungsten with high thicknesses from 80 cm to 60 cm, upstream to downstream, in order to accommodate the high radiation emerged from the interaction of the 15 MW proton beam and the liquid Hg-jet. The high coil-to-coil apertures are about 2 m thus leaving the space for the heavy shielding and the required volume for free spiralling of pions. For the given field of 14 T at the interaction area, 40 cm aperture of free magnetic volume is enough to capture and transport high energy pions in order to produce the best muon beam [2]. The schematic layout of the solenoid is shown in Figure 1.

## 2. Multi-MW Target Systems

In order to make next generation accelerator neutrino and muon experiments we need to invent a new targetry system that could accept a multi-MW primary proton beam power in order to produce high intensity neutrino and muon beams. At MOMENT, the liquid Hg-jet target of Neutrino Factory has been adapted, which was studied at MERIT, CERN [3, 4]. High heat load and radioactivity will be produced at the target station because of high proton beam power of 15 MW but without the presence of shock-waves due to the application of a continuous (CW) proton linac [5].

In searches for physics beyond the standard model such as leptonic CP-violation and new particles, accelerator neutrino experiments and future projects are using proton drivers with increased power. Current experiments T2K and NOvA have less than 1 MW drivers, future T2HK, LBNF/DUNE are foreseen with up to 1.3 MW ones, while MOMENT, a Neutrino Factory or a Muon Collider require 4 MW and greater ones in order to produce the highest intensity neutrino and muon beams [6]. For the most intense beams, the best principle for the targetry is flowing types with liquids or granules because of their ability to dissipate high energy densities and heat, be cooled externally, and finally be recirculated. The objective is to study new targets operating inside strong magnetic fields in terms of their physics potentialities and design, in order to understand if they are feasible and applicable to the multi-MW abovementioned projects.

## 3. Liquid Hg-jet

The optimization studies in terms of pion and muon yields of the Hg-jet target for MOMENT have shown that a liquid jet with an interaction length of 30 cm, radius of 5 cm or more that follows the 3 to 4 times the beam size rule, and a slight tilt of 100 mrad in respect to the magnetic beam lines, would give rise downstream of a muon beam with a high intensity of $10^{22}$ $\mu^+$/year at a 15 MW proton power [1, 2, 7]. In addition, a polynomial cubic representation will been chosen for the target station adiabatic field of 14 T to 3 T in order to achieve maximum shielding thickness.

Initial radiation studies have been focused on the protection of the coils and the cooling of the shields [8] and performed with FLUKA Monte Carlo [9]. By using a maximum tungsten thickness of 80 cm, the total energy deposition on each of the five coils is less than 1 kW. The total power on the shield is 10 kW and could be removed effectively by using a multiple pipe channel system with water or He as coolants. Those studies also have shown that there is a high neutron flux on the coils about $10^{21}$ n/m$^2$/year that reduces the electrical and thermal conductivity of the aluminium stabilizers in the superconductor wire, which could be resolved with appropriate thermal cycles of the magnets to room temperature. In addition, high structural radiation damage ($dpa$) on the surroundings of Hg-jet will lead to the deterioration of the shield [10]. So a strategy of protecting or changing that part of the shield has to be studied in future.

## 4. Compact Granular Waterfall

The concept of a compact granular waterfall target is attractive because of its simple principle of operation in which the motion of the granules is driven by gravity. Also, a compact geometry is needed in order to fit the solenoids of MOMENT, Neutrino Factory or Muon Collider compared to current designs of large granular waterfall or jet targets [11, 12]. The toxicity of Hg presents a major disadvantage for a jet inside a superconducting solenoid with the collecting pool, and in a recirculation circuit. Furthermore, there is the questionable jet stability of Hg since it is required to have a velocity of 70 m/s in order to accommodate the 15 MW of proton power at MOMENT.

In principle, a granular waterfall target has several advantages over a liquid jet such as high flow rate and large cross section that lead to high power densities absorbed and removed, reliable and simple circuit with gravity driven flow of granules, no cavitation/splashing or spiked jets, and with any shock waves constrained within material grains.

A preliminary compact granular waterfall target has been studied for MOMENT demonstrating in simulation the abovementioned advantages [13]. The schematic geometry of this novel target is shown in Figure 2. The main components are tungsten carbide granules with extremely

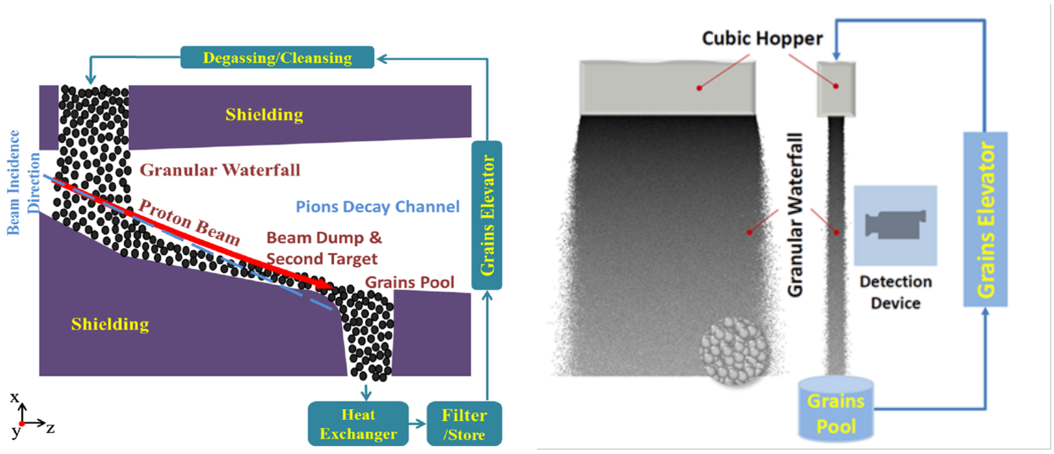


**Figure 2:** Schematic representation of the granular waterfall target and its circuit.

low magnetic susceptibility and electrical conductivity in order to avoid the shape transformations and instabilities of the grain waterfall at 14 T. The recirculation circuit includes a grain pool, heat exchanger, filter, grain elevator and a degassing/cleansing system. Due to the granular and waterfall form of the target the effective density is reduced as a function of its height and width and it depends on the cross section of the cubic hopper at which the grains enter in the empty magnetic volume in order to interact with the proton beam.

Physical parameters such as effective densities, mass flow rate and velocities of the granular waterfall, and the related heat removal were studied by applying a combined GPU based discrete element method analysis (DEM) and GEANT4 Monte Carlo [13, 14]. In those, the granular waterfall shows superior heat removal compared to liquid-Hg and granular-tungsten jet targets [13]. The schematic represenation of the proton beam and waterfall target interaction, and the effective densities as function of cubic hopper width are shown in Figure 3.

## 5. Particle Yields

Initially a toy model of a tungsten granular waterfall target indicated that the pion yields are not restrained by the reduced density and geometry of the waterfall, thus showing the potential to be used as alternative target [7].

Our latest studies show that our optimized liquid Hg-jet and the granular waterfall targets have comparable charged pion yields at the target area and about 20% different muon yields at the end of the pion decay section, the waterfall produces the reduced yields. A compact geometry with a waterfall target length from 20 cm to 35 cm and a cubic hopper width from 3 cm to 4 cm is optimum in order to achieve those yields. It has to be pointed out that those results have been made by the combined analysis of the granular waterfall target effective densities for each hopper width as calculated by the GPU based DEM program, which in turn used as input to GEANT4 as at [13]. Our relative statistical error for the abovementioned comparison is about 1% and 2% for pion and muon yields respectively. The systematic errors from not simulating the exact granular structure in GEANT4 are expected to be small due to the compact dimensions of the waterfall, and will be studied in the future.

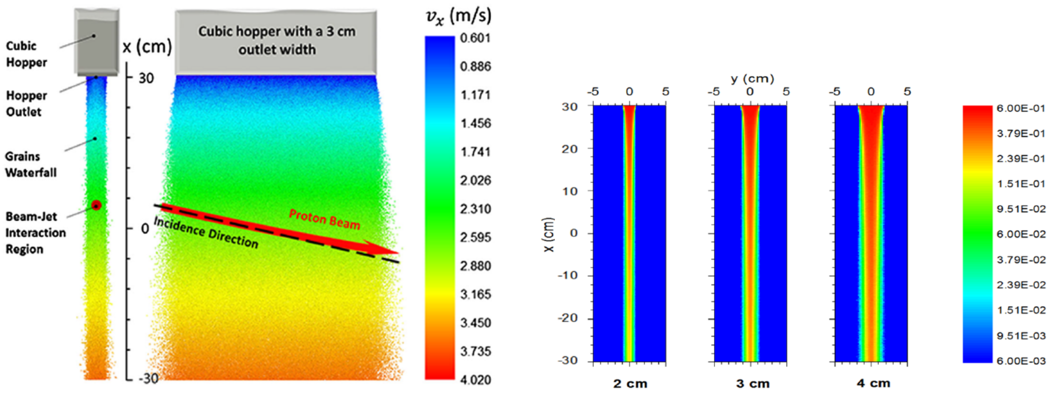


**Figure 3:** Schematical representation of beam-waterfall interaction with grains velocities (left plot), and the medium density (relative factor) distributions (in x-y plane) for waterfalls with 2 cm, 3 cm and 4 cm cubic hopper widths (right plot). Taken from [13].

## 6. Conclusions

The compact granular waterfall target has the potential to be a candidate for the future high intensity neutrino and muon beams as MOMENT, Neutrino Factory or Muon Collider. Our preliminary simulation studies indicate that it has all the characteristics for an efficient heat removal and operation as well as a comparable production of charged pion and muon yields with the liquid Hg-jet target. Both MOMENTs target group at IHEP [15] and C-ADS target group at IMP [16] in collaboration have foreseen further simulations and an experiment, and in order to study the feasibility of that novel granular waterfall target.

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