Radiation Studies for the Target Station of MOMENT (Postprint)

Authors: Qing-Nian Xu, Jian-Fei Tong, Nikolaos Vassilopoulos, Jun Cao, Miao He, Zhi-Long Hou, Han-Tao Jing, Huai-Min Liu, Xiao-Rui Yu, Jing-Yu Tang, Ye Yuan, Guang Zhao, Yang-Heng Zheng

Date: 2016-09-02T00:00:00+00:00

Abstract

The discovery of the neutrino mixing angle 13 opens new opportunities for the discovery of the leptonic CP violation for high intensity neutrino beams. MOMENT a future neutrino facility with a high-power proton beam of 15 MW from a continuous-wave linac is focused on that discovery. The high power of the proton beam causes extreme radiation conditions for the facility and especially for the target station where the pion capture system of five superconducting solenoids is located. In this paper initial studies are performed for the effects of the radiation on the solenoid structure and the area surrounding it. A concept cooling system is also proposed.

Full Text

Preamble

Chinese Physics C Vol. xx, No. x (201x) xxxxxx

Radiation Studies for the Target Station of the MOMENT

Qing-Nian Xu[1;1)], Jian-Fei Tong[2], Nikolaos Vassilopoulos[2], Jun Cao[1], Miao He[2], Xiao-Rui Lyu[1], Zhi-Long Hou[2], Han-Tao Jing[2], Huai-Min Liu[2], Guang Zhao[2], Jing-Yu Tang[2], Ye Yuan[2;2)], Yang-Heng Zheng[1;3)]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: The discovery of the neutrino mixing angle 13 opens new opportunities for discovering leptonic CP violation with high-intensity neutrino beams. MOMENT, a future neutrino facility featuring a 15 MW continuous-wave proton linac, is designed to pursue this discovery. The high beam power creates extreme radiation conditions throughout the facility, particularly at the target station where the pion capture system comprises five superconducting solenoids. This paper presents initial studies on radiation effects on the solenoid structure and surrounding areas, and proposes a conceptual cooling system.

Key words: MOMENT, High intensity beam, Neutrino, Target station, Radiation damage
PACS: 29.25.-t, 29.38.Db, 29.20.Ej

Received xx Apr. 2016
Supported by National Natural Science Foundation of China (11425524, 11527811, 11575226) and Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA10010100).
[1]) E-mail: xuqingnian10@mails.ucas.ac.cn
[2]) E-mail: yuany@ihep.ac.cn
[3]) E-mail: zhengyh@ucas.ac.cn

1.1 MOMENT

In recent years, neutrino physics has made remarkable progress. The Daya Bay experiment determined the last neutrino mixing angle 13 to be non-zero in 2012 [1]. The large value of 13 opens opportunities to discover leptonic CP violation and determine the neutrino mass hierarchy using future neutrino super-beams [2–4]. Leptonic CP violation is a necessary ingredient to explain the observed matter dominance in the universe, as the measured CP violation in the quark sector is insufficient to account for the matter-antimatter asymmetry [5, 6].

[Figure 1: see original paper] Layout of the MOMENT facility [7].

MOMENT (MuOn-decay MEdium-baseline NeuTrino beam) [7] is a future facility dedicated to measuring the CP phase using neutrinos from muon decays. It employs a 15 MW continuous-wave (CW) 1.5 GeV proton beam provided by the China-ADS linac [8]. Pions are produced through interactions between the proton beam and a liquid mercury jet target immersed in a high magnetic field generated by a capture superconducting solenoid. High-energy protons escaping the interaction region are absorbed by a beam dump near the target station. Following this, a 50 m pion-decay line is designed where pions decay into muons and neutrinos. Subsequently, a muon charge selection system and bending transport section are being designed to separate the directions of muons and pion-decay neutrinos. The final part of the beamline consists of an adiabatic transport section and a 600 m long muon decay channel designed to focus muons toward the detector direction and allow them to decay into neutrinos. The average neutrino beam energy is E = 300 MeV, with the detector planned to be located 150 km from the facility. The layout of the MOMENT experiment is shown in Fig. 1.

1.2 Target Station

At the target station, pions are generated from protons colliding with the mercury target and are then collected and transported by adiabatic magnetic fields produced by five superconducting (SC) solenoids. Due to the extremely high radiation, large amounts of heat will be deposited on the solenoid elements, and radiation damage will be induced. Therefore, a tungsten cylindrical shield is necessary to protect the five solenoids, and the geometry design of the target station strongly depends on the limits established by radiation studies.

[Figure 2: see original paper] Layout of the MOMENT pion capture system solenoid [7].

The target station primarily consists of the target and solenoid, as shown in Fig. 2. Solid targets used in conventional (low-intensity) neutrino beams cannot withstand such high beam power, so fluid targets such as liquid or powder jets and waterfalls are being investigated. Their main advantages include minimal material damage and high heat absorption and transfer due to their recycling nature. At MOMENT, the nominal mercury jet target is placed in a high-field superconducting solenoid [9]. A 14 T field is used to capture charged mesons with high efficiency, followed by a slow adiabatic decrease from 14 T to 3-4 T to reduce their transverse momentum (relative to the beam-line direction) and maximize transport efficiency. To produce these fields, five superconducting solenoids are used with a total length of about 7.3 m and a radius of about 1 m, constructed from Nb3Sn and NbTi wires as summarized in Table 1. A tungsten shield with a maximum (minimum) thickness of 77.5 (57.8) cm at the beginning (end) is placed between the target and the solenoid. This solenoid configuration is proposed in [7] and is studied in this paper. FLUKA Monte Carlo [10, 11] is used to study energy deposition, radiation damage, and activation for the tungsten shield and superconducting solenoids.

Geometrical characteristics of the superconducting solenoids.

[Figure 3: see original paper] Transverse view of the tungsten shield and the five superconducting solenoids from FLUKA simulation.

2 Energy Deposition

The energy deposited on the shield and solenoid is calculated. The primary mechanisms of energy deposition are atomic ionization by heavy charged particles, electromagnetic showers from electrons and gammas [12], and nuclear interactions of neutrons. The shield is needed to protect the superconducting solenoids (Nb3Sn, NbTi [13]) from heating and structural damage. The transverse view of the simulated geometry in FLUKA is shown in Fig. 3.

The energy deposition density in the materials is shown in Fig. 4. The total energy deposition on the shield is about 10 MW, with maximum volumetric heat exceeding 100 W/cm^3 around the mercury target area and along the inner part of the shield. The energy deposition in the superconducting solenoids is limited to below 1 kW, which is acceptable for the cryogenic system of the coils.

[Figure 4: see original paper] Energy deposition density as a function of depth for the shield and superconducting solenoids.

3 Cooling Structure

A Multiple Rows of Mini-Channel (MRMC) cooling structure is designed for the tungsten shield, as shown in Fig. 5. The cooling channel dimensions are 1 cm × 1 cm, and the first wall thickness (the distance from the channel to the inner wall of the shield) is about 1 cm. The channel shape in the shield was designed to remove the highest volumetric heat. The volume ratio of cooling channels is 1% compared to the total shield volume.

[Figure 5: see original paper] Geometry of shield with cooling channel; (a) 3D view of shield; (b) cut view at x=0.

A three-dimensional simulation of conjugate heat transfer with fluid flow in ANSYS CFX is carried out for the shield, compiling a corresponding FORTRAN program to describe the non-uniform heat source distribution. The standard k-model is used for turbulent dissipation in this calculation. The model is shown in Fig. 6. The mesh numbers for the solid and fluid domains are 1.3 million and 0.6 million respectively, with grid dependence verified. Water at 3 atm and helium at 30 atm are examined as possible cooling solutions. The inlet temperature is 300 K, and the coolant velocity in each channel inlet is 5 m/s for water and 50 m/s for helium. The thermal parameters of materials are shown in Table 2.

Thermal parameters of materials.

With the MRMC structure and water as coolant, when the mass flow rate is 3.49 kg/s for this domain, the maximum temperature of the shield is less than 384 K. The pressure drop is 0.8 MPa and the outlet temperature is 311 K. The water cooling results are shown in Fig. 7. With high-pressure helium at high velocity, when the mass flow rate is 0.15 kg/s for this domain, the maximum temperature of the shield is below 900 K, the pressure drop is 0.54 MPa, and the outlet temperature is 519.3 K. The helium cooling results are shown in Fig. 8. These results demonstrate that with the MRMC structure and either water or pressurized helium as coolants, the maximum temperatures in the shield remain below 800°C, thus meeting the tungsten cooling requirements, albeit with high coolant pressure drops.

[Figure 6: see original paper] Calculation domain for the shield.

[Figure 7: see original paper] Temperature distribution of the shield with water cooling.

[Figure 8: see original paper] Temperature distribution of the shield with pressurized helium cooling.

4 Radiation Damage

Under 15 MW proton beam interactions with the mercury target, severe radiation occurs in the space surrounding the target and particularly in different parts of the solenoid. The radiation-induced damage for the shield and superconducting solenoids is calculated in terms of average displacements per atom (dpa), which are caused by neutrons, charged particles, and high-energy photons, using FLUKA Monte Carlo. The neutron flux is shown in Fig. 9.

[Figure 9: see original paper] Neutron flux distribution as a function of depth in the target station.

The maximum neutron flux is estimated to be about 2×10^{22} and 2×10^{21} n/m^2/year for the first two superconducting solenoids (Nb3Sn) and the remaining three (NbTi), respectively.

[Figure 10: see original paper] Displacement damage per proton on target. The maximum dpa occurs around the mercury target and the first SC solenoid, then decreases as a function of solenoid length.

The dpa per proton on target for the five superconducting solenoids is shown in Fig. 10. The largest values are found around the mercury target and in inner locations. The dpa distribution as a function of radius of the first superconducting solenoid for one year of operation* is shown in Fig. 11. The maximum value is about 3.2×10 dpa after one year of operation. This is a small value that does not raise concerns for the operation of the five superconducting solenoids, demonstrating that the shield provides effective protection. The situation for the tungsten shield is entirely different, as shown in Fig. 12 for one year of operation. The value of 2.46 dpa is concerning. This high value, when compared for example with results obtained at Los Alamos National Laboratory [15], indicates deterioration of the inner part of the tungsten shield and necessitates periodic replacement.

[Figure 11: see original paper] Displacement damage dependence as a function of depth for the first superconducting solenoid. The dpa results are normalized by the number of protons for 1 year.

[Figure 12: see original paper] Displacement damage dependence as a function of depth for the shield. The dpa results are normalized by the number of protons for 1 year.

*For one year, 208 operational days for the accelerator are assumed, with 6.12×10^{1} protons on target expected for a 15 MW, 1.5 GeV proton beam.

5 Study of Dose Effective Rate and Activation

The prompt and remnant dose effective rates are calculated in areas surrounding the solenoid to assess radiation levels. The prompt dose rate reaches 9.9×10 , 4.2×10^{1} , and 5.6×10 mSv/h in the areas above, upstream, and downstream of the solenoid, respectively, as shown for the former in Fig. 13. For the floor above the solenoid, future studies are needed to define the depth and composition of shielding to reduce dose rates to acceptable limits at Sv/h levels according to radiation protection regulations [16]. The remnant dose rate is also calculated after one year of irradiation for cooling times of one day, one week, one month, and four months. These values are measured in a small volume above the center of the superconducting solenoids and are shown in Fig. 13. The remnant dose rate decreases with cooling time as expected, but remains high after four months, on the order of mSv/h. With additional shielding surrounding the experimental layout, these values would be expected to decrease to radiation protection limits.

[Figure 13: see original paper] Prompt (a) and remnant (b) dose effective rates in the space above the SC solenoids. For the former, the distribution along the solenoids is presented. For the latter, the value is for a small volume above and in the middle for four cooling times after one year of operation.

Finally, the total activation for the shield is shown in Fig. 14. The maximum value reaches 14×10^{1} Bq.

[Figure 14: see original paper] Activation of the shield for six cooling times after one year of radiation. The maximum value reaches 14×10^{1} Bq.

6 Conclusion

MOMENT utilizes a high-power 15 MW beam from a CW linac, which presents a significant challenge for any target station and collection scheme due to intense radiation. Sophisticated shielding is necessary to protect the superconducting solenoids. Calculations of energy deposition in the shield, superconductors, and cryostat have been performed, and a cooling structure for the inner shield using either water or high-pressure helium has been studied. The primary concern arises from radiation damage to the shield. The displacements per atom calculations indicate that fractures will develop in the shield, necessitating periodic replacement. The low radiation damage values for the solenoid wire materials demonstrate that the shield protection is highly effective. Prompt and remnant dose effective rates have also been calculated above the solenoid. Consequently, heavy shielding surrounding the solenoids must be studied to reduce dose rate values to within radiation protection limits.

References

1. Daya Bay Collaboration (An, F.P. et al.) Phys. Rev. Lett. 112 (2014) 061801 arXiv:1310.6732 [hep-ex]
2. M. B. Gavela, P. Hernandez, J. Orloff and O. Pene, Mod. Phys. Lett. A 9 (1994) 795 [hep-ph/9312215, hep-ph/9312215].
3. M. B. Gavela, P. Hernandez, J. Orloff, O. Pene and C. Quimbay, Nucl. Phys. B 430 (1994) 382 [hep-ph/9406289]
4. J. Cao et al., Phys. Rev. ST Accel. Beams 17, 090101 (2014), 1401.8125.
5. Bennett, J. Roger J. et al. CERN-INTC-2004-016, CERN-INTC-P-186

6. G. Battistoni et al., in Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab, edited by M. Albrow and R. Raja, AIP Conf. Proc. No. 896 (AIP, New York, 2007), pp. 31-49.
7. A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, Reports No. CERN-2005-10, No. INFN/TC 05/11, and No. SLAC-R-773,
8. Techniques for Nuclear and Particle Physics Experiments: A How to Approach - Leo, W.R. Berlin, Germany: Springer (1987) 368 p ISBN-9783540572800
9. S.A. Maloy, M.R. James, W.F. Sommer jr., APT/TPO, MS H809 G.J. Willcutt, jr., D-10, MS K575 M.R. Lopez, T.J. Romero NMT-11, MS G742
10. A. V. Zlobin, IEEE/CSC & ESAS European Superconductivity radiation and for the safety of radiation sources News Forum (ESNF), No. 16, 2011.

Note: Figure translations are in progress. See original paper for figures.