Radiation studies for the MOMENT target station *

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Abstract: The discovery of the neutrino mixing angle θ_{13} opens new opportunities for the discovery of leptonic CP violation at 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.

Keywords: MOMENT, high intensity beam, neutrino, target station, radiation damage

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1 Introduction

1.1 MOMENT

In recent years, neutrino physics has made substantial progress. The last neutrino mixing angle θ_{13} was determined to be non-zero by the Daya Bay collaboration [1] in 2012. The large value of θ_{13} opens the opportunity to discover leptonic CP-violation and detect the neutrino mass hierarchy at future neutrino superbeams [2–4]. Leptonic CP violation is a necessary ingredient to generate the observed matter dominance in the universe, since the measured CP violation in the quark sector is not enough to account for the matter-antimatter asymmetry in the universe [5, 6].

MOMENT (MuOn-decay MEdium-baseline NeuTrino beam) [7] is a future facility focused on the CP phase measurement using neutrinos from muon decays. MOMENT uses a 15 MW continuous-wave (CW) 1.5 GeV proton beam provided by the China-ADS linac [8]. Pions are generated from interactions between the proton beam and a liquid mercury jet target immersed in a high magnetic field from a capture superconducting solenoid. High energy protons escaping the interaction region are absorbed by a beam dump near the target station. After that, a 50 m pion-decay line where pions decay to muons and neutrinos is designed. Thereafter a muon charge selection system and a bending transport section in order to separate the direction of the muons and the pion decay neutrinos is being designed. The last part of the beamline consists of an adiabatic transport section and a long muon decay channel of 600 m designed to focus the muons towards the detector direction and allow them to decay to neutrinos. The average neutrino beam energy is $< E_\nu > = 300$ MeV. The

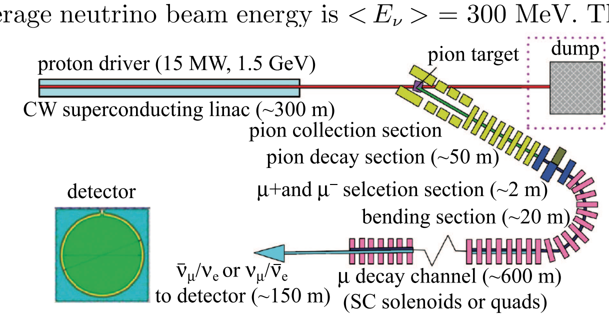

Fig. 1. (color online) Layout of the MOMENT facility. From Ref. [7], J. Cao et al, "Muon-decay medium-baseline neutrino beam facility", DOI: 10.1103/PhysRevSTAB.17.090101.

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detector is foreseen to be located 150 km far away 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 elements of the solenoids. In addition, radiation damage will be induced. Therefore, a tungsten cylindrical shield is necessary to protect the five solenoids. The geometry design of the target station is then strongly dependent on the limits set from radiation studies.

The target station mainly consists of the target and the solenoid as shown in Fig. 2. Solid targets used in conventional (low intensity) neutrino beams could not withstand such high beam power so fluid targets such as liquid or powder jets and waterfalls are being studied. Their main advantages are minimum 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 the charged mesons with high efficiency and then a slow adiabatic decrease is implemented from 14 T to 3–4 T in order to reduce their transverse momentum (with respect to the beam-line direction) and maximize their transport efficiency. In order to produce these fields, five superconducting solenoids are used with a total length of about 8.3 m and a radius of about 1 m, made from Nb_3Sn 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 Ref. [7] and is studied in this paper. FLUKA Monte Carlo [10, 11] is used

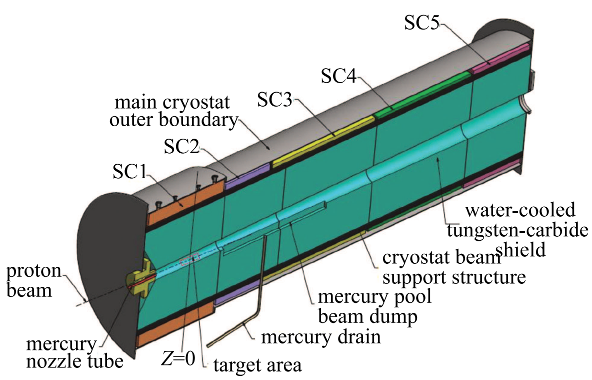

Fig. 2. (color online) Layout of the MOMENT pion capture system solenoid. From Ref. [7], J. Cao et al, "Muon-decay medium-baseline neutrino beam facility", DOI: 10.1103/PhysRevSTAB.17.090101.

Table 1. Geometrical characteristics of the superconducting solenoids.

	material	Z/m		R/m	
		from	to	inner	outer
SC 1	Nb_3Sn	−0.7	0.99	1.05	1.23
SC 2		1.04	2.08	1.05	1.14
SC 3	NbTi	2.13	4.33	1.05	1.13
SC 4		4.38	6.58	1.05	1.11
SC 5		6.63	7.63	1.05	1.14

to study the energy deposition, radiation damage and activity of the tungsten shield and the superconducting solenoids.

2 Monte Carlo simulation with FLUKA

FLUKA Monte Carlo is used to simulate hadronic and electromagnetic interactions for a number of experiments. It is one of the main codes used for radiation studies and safety calculations for energy depositions and radiation damage in materials along with particle fluxes and dose rates. It is continuously validated with data from low energy nuclear physics, high energy experiments and atmospheric fluxes. FLUKA uses a resonance model to simulate hadron-nucleon interactions below a few GeV whereas the Dual-Parton Model (DPM) is used above that level. The hadron-nucleus interactions are treated with the PreEquilibrium Approach to NUclear Thermalization model, including the Gribov-Glauber multi-collision mechanism followed by the pre-equilibrium stage and eventually equilibrium processes (evaporation, fission, Fermi break-up and gamma deexcitation). FLUKA can simulate particles with a broad range of energies, including thermal neutrons, as they pass through matter [12]. For the calculation of the dpa in material, FLUKA uses an equivalent partition function to the Lindhard one applied in other codes, with reworked formulas and restrictions in energy above a user defined damage threshold [13]. The energy deposition, radiation damage and activity is calculated with mesh of Z:R:ϕ=1 cm : 1 cm : 2π and biasing method is not used in the calculation [14].

3 Energy deposition

The energy deposited on the shield and the solenoid is calculated. The primary mechanism of the energy deposition is the ionization of the atoms by heavy charged particles, electromagnetic showers by electrons and gammas [15] and nuclear interactions of neutrons. The shield is needed to protect the superconducting solenoids (Nb_3Sn, NbTi [16]) from heating and structural damage. A transverse view of the simulated geometry in FLUKA is shown in Fig. 3. The energy deposition density on the materials is shown in Fig. 4. The total energy deposition on the shield is about 10 MW and the maximum volumetric heat is above 100 W/cm^3 around the mercury target area and along the inner part of the shield. The energy deposition in superconducting solenoids is limited below 1 kW, which is acceptable for the cryogenic system of the coils.

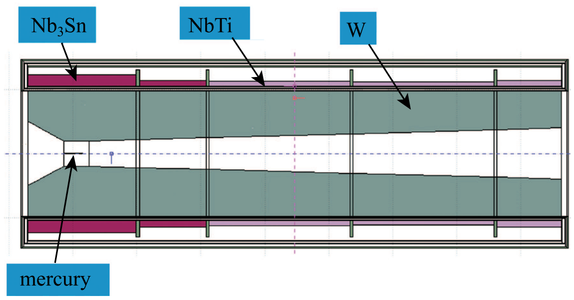

Fig. 3. (color online) Transverse view of the tungsten shield and the five superconducting solenoids from FLUKA simulation.

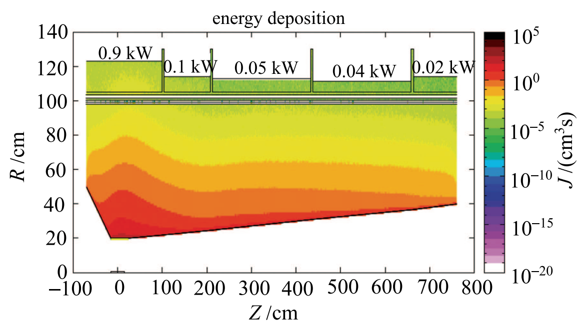

Fig. 4. (color online) Energy deposition density as function of depth for the shield and superconducting solenoids.

4 Cooling structure

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

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

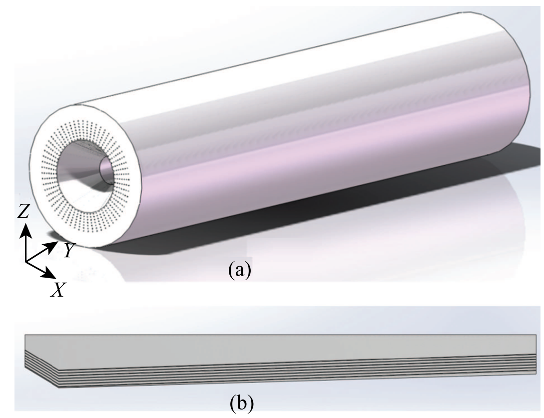

Fig. 5. (color online) Geometry of shield with cooling channel; (a) 3D view of shield; (b) cut view of $x=0$.

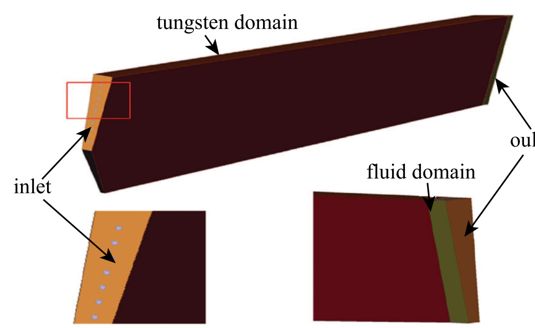

Fig. 6. (color online) Calculation domain for the shield.

Table 2. Thermal parameters of materials.

	K/ (W/m·K)	Cp/ (J/kg·K)	viscosity (Pas)	density/ (kg/m^3)
water	0.61	4181.7	8.90×10^{-4}	9.97×10^{2}
helium@ 30 atm& 300 K	0.16	5181.0	2.01×10^{-5}	4.78
tungsten	1.2×10^{2}	132.0		1.94×10^{4}

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 500 K, and the maximum temperature of water is 384 K. The pressure drop is 0.8 MPa and the outlet temperature is 311 K. The results of water cooling 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 results of helium cooling are shown in Fig. 8. The results show that with the MRMC structure and water or pressurized helium as coolants, the maximum temperatures for the shield are below 800 degrees, thus meeting the tungsten cooling demands although with high coolants the pressure drops.

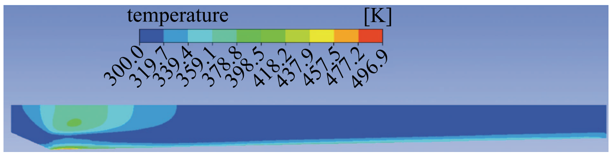

Fig. 7. (color online) Temperature of the shield with water cooling.

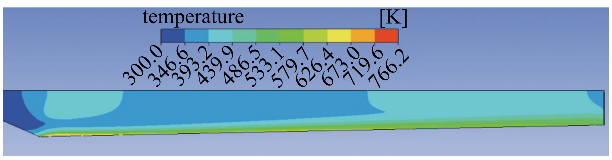

Fig. 8. (color online) Temperature of the shield with pressurized helium cooling.

5 Radiation damage

With 15 MW proton beam interactions with the mercury target, there is severe radiation in the space surrounding the target and especially in the different parts of the solenoid. The radiation induced damage for the shield and the superconducting solenoids is calculated in terms of the average displacements of each atom (dpa), which are caused by neutrons, charged particles and high energy photons, and is calculated by FLUKA Monte Carlo. The neutron and charged particle fluxes are shown in Fig. 9. There is estimated to be a maximum neutron flux of about 2×10^{22} for the first two superconducting solenoids (Nb_3Sn) and 2×10^{21} n/m^2/year for the remaining three (NbTi). Damage to Nb-based superconductors appears to become significant at doses of 2–3$\times10^{22}$ n/m^2 [17]. Reviews of these considerations for ITER can be found in Ref. [18].

The dpa per proton on target for the five superconducting solenoids is shown in Fig. 10. The largest values are calculated to be around the mercury target and in the inner locations. The distribution of dpa as a function of radius of the first superconducting solenoid for one year of operation [1)] is shown in Fig. 11. The maximum value is about 3.2×10^{-4} dpa after one year of running. The superconductor solenoids mainly consist of superconducting wire (Nb_3Sn/NbTi) and an aluminum layer. Damage to the aluminum can be recovered by thermal cycling to room temperature [19]. The situations for the superconducting solenoids without shield protection and with a tungsten shield are totally different. The results are shown for one year of running in Fig. 12. The values of 0.40 dpa and 2.46 dpa for superconducting solenoids and tungsten shield are of concern. These are high values and the dpa for the shield is compared for example with the

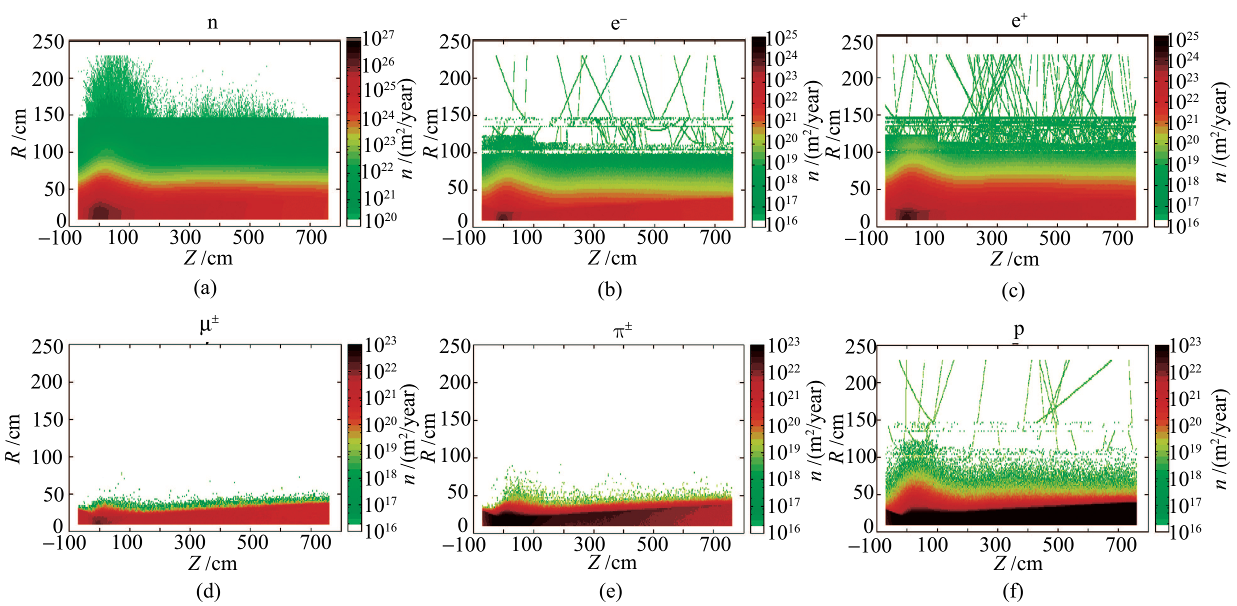

Fig. 9. (color online) Neutron (a), electron (b), positron (c), muon (d), pion (e) and proton (f) flux distributions as a function of depth in the target station.

1)For a year, 208 operational days for the accelerator are taken and a proton beam of 15 MW and 1.5 GeV kinetic energy with 1.1×10^{24} p.o.t. is expected.

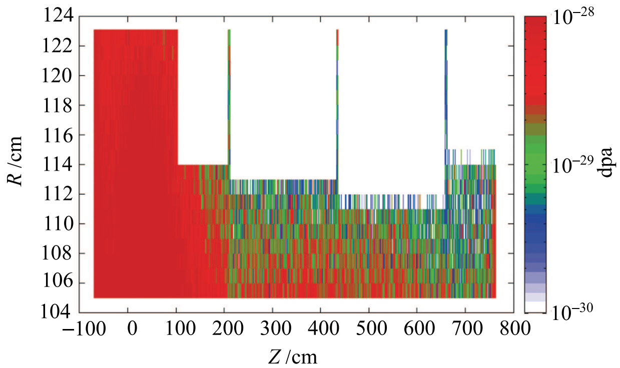

Fig. 10. (color online) Displacement damage per proton on target. The maximum dpa is around the mercury target and the first SC solenoid, then it reduces as a function of the length of the solenoid.

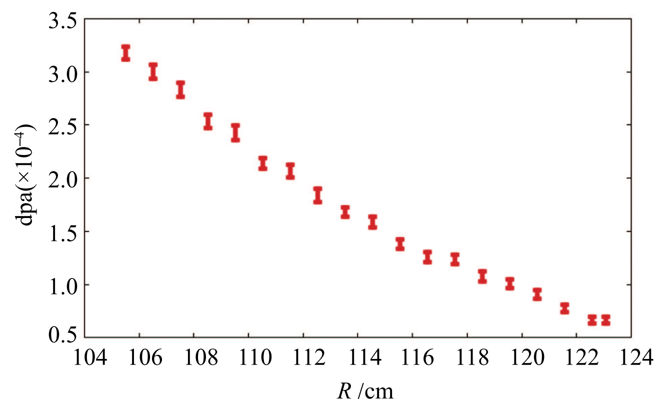

Fig. 11. (color online) Displacement damage dependence as function of depth for the first superconducting solenoid. The dpa results are normalized by the number of protons for 1 year.

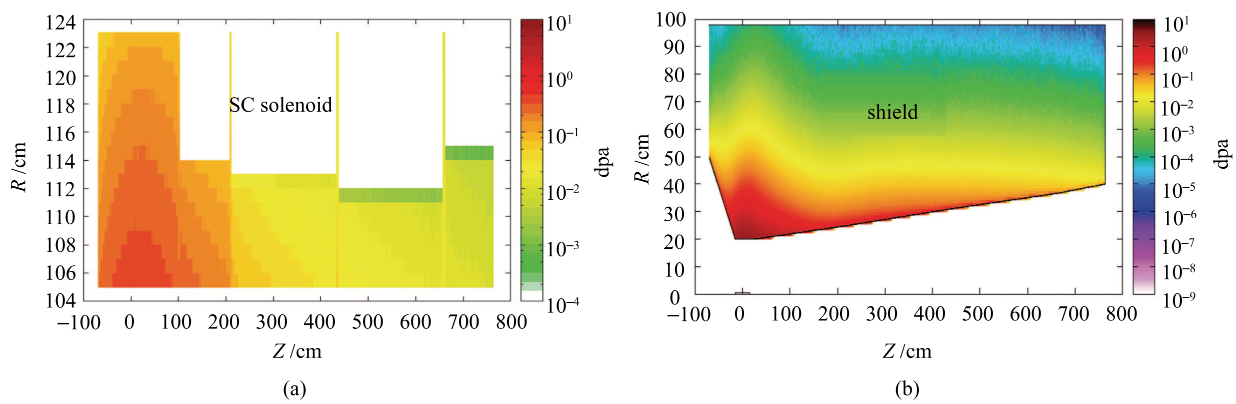

Fig. 12. (color online) Displacement damage dependence as function of depth for the SC solenoid without shield protection (a) and with the shield (b). The dpa results are normalized by the number of protons for 1 year.

results obtained in Los Alamos National Laboratory [20]. It indicates deterioration of the inner part of the tungsten shield and the need to replace it periodically.

6 Study of effective dose rate and activity

The prompt and remnant effective dose rates are calculated in the surrounding areas of the solenoid in order to examine their radiation levels. The prompt dose rate reaches 8.9×10^{6}, 4.2×10^{10} and 5.6×10^{9} mSv/h in the areas above, upstream and downstream of the solenoid respectively, as shown in Fig. 13. For the floor above the solenoid, future studies are needed to define the depth and the composition of the shield in order to lower the dose rates to acceptable limits at μSv/h levels, in accordance with the radiation protection rules [21]. The remnant dose rate is also calculated after one year of irradiation and for a day, a week, a month and four months of cooling time. They are measured at a small volume above the center of the superconducting solenoids and are shown in Fig. 13. The value of the remnant dose rates as a function of cooling time decreases, as expected, but the values are still high after four months, of the order of mSv/h. This level of radiation exposure is dangerous for maintenance workers, so remote maintenance is advised. With the addition of the shield surrounding the experimental layout these values would be expected to decrease to within radiation protection limits. Finally, the total activity of the shield is shown in Fig. 14. This work is still preliminary and more work will be done in the future.

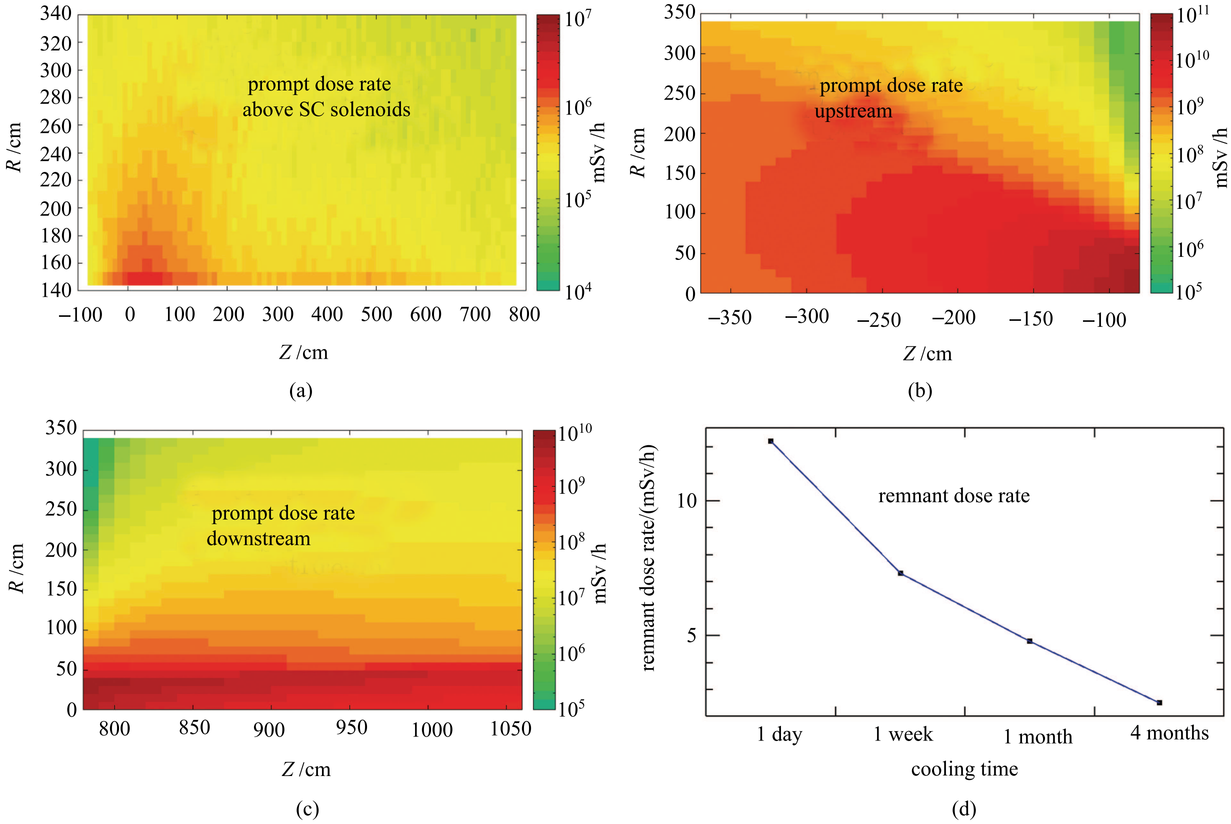

Fig. 13. (color online) Prompt (a),(b),(c) and remnant (d) effective dose rates in the space beyond the SC solenoids is calculated with the EWT74 fluence-to-effective dose conversion coefficients. For the remnant dose rates the value is for a small volume above and in the middle for four cooling times after one year of operation.

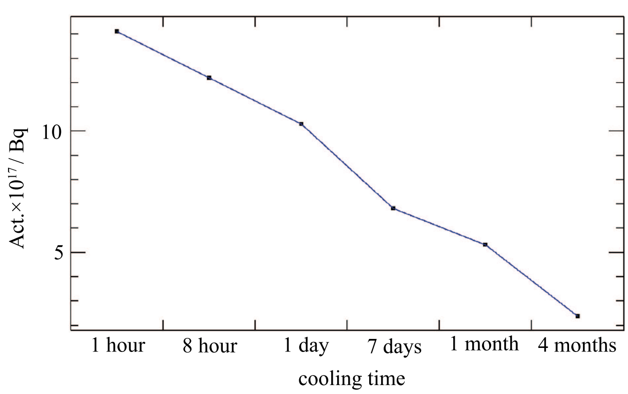

Fig. 14. Activity of the shield for six cooling times after one year of radiation. The maximum value reaches 14×10^{17} Bq.

7 Conclusion

MOMENT uses a high-power beam of 15 MW from a CW linac, which is a challenge for any target station and collection scheme due to the high radiation. A sophisticated shielding system is necessary to protect the superconducting solenoids. The energy deposition in the shield, superconductors and cryostat has been calculated, and a cooling structure for the inner shield by using either water or high-pressure helium has also been studied. The problem arises from the radiation damage to the shield. The displacement per atom calculations indicate that fractures will be created on the shield and thus periodic replacement is necessary. The low values of the radiation damage for the solenoid wire materials indicate that the shield protection is highly effective. The prompt and remnant effective dose rates were also calculated above the solenoid. As a result, heavy shielding surrounding the solenoids has to be studied in order to keep the dose rates values within radiation production limits.

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