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ENERGY PRODUCTION DEMONSTRATOR AND MATERIAL TESTING STATION OPTIMIZATION FOR MEGAWATT PROTON BEAMS[1]

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Abstract

A simulation study of the Energy Production Demonstrator (EPD) concept a solid heavy metal target irradiated by GeV-range intense proton beams and producing more energy than consuming - is carried out. Neutron production, fission, energy deposition, energy gain, testing volume and helium production are simulated using the MARS15 code for tungsten, thorium, and natural uranium targets in the proton energy range 0.5 to 120 GeV. This study shows that the proton energy range of 2 to 4 GeV is optimal for both a ^{nat}U EPD and the tungsten-based testing station for proton accelerator facilities. Simulation based conservative estimates not including breeding and fission of plutonium suggest the proton beam current sufficient to produce 1 GW of thermal output power with the ^{nat}U EPD while supplying a relatively small fraction of that power to operate the accelerator. The thermal analysis has been performed and has shown that the EPD with a parallel proton beam feeding the core has a potential problem due to a possible core meltdown. A scheme has been proposed with a beam steering on the outer surface of the target; its thermal analysis indicates that slicing the target in shorter parts and maintaining a temperature of 25° C on their surfaces would to avoid the target meltdown.

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A simulation study of the Energy Production Demonstrator (EPD) concept - a solid heavy metal target irradiated by GeV-range intense proton beams and producing more energy than consuming - is carried out. Neutron production, fission, energy deposition, energy gain, testing volume and helium production are simulated using the MARS15 code for tungsten, thorium, and natural uranium targets in the proton energy range 0.5 to 120 GeV. This study shows that the proton energy range of 2 to 4 GeV is optimal for both a ^{nat}U EPD and the tungsten-based testing station for proton accelerator facilities. Simulation-based conservative estimates not including breeding and fission of plutonium suggest the proton beam current sufficient to produce 1 GW of thermal output power with the ^{nat}U EPD while supplying a relatively small fraction of that power to operate the accelerator. The thermal analysis has been performed and has shown that the EPD with a parallel proton beam feeding the core has a potential problem due to a possible core meltdown. A scheme has been proposed with a beam steering on the outer surface of the target; its thermal analysis indicates that slicing the target in shorter parts and maintaining a temperature of 25°C on their surfaces would to avoid the target meltdown.

1. Introduction

Possibilities for applications of high-energy proton beams for energy production has attracted attention during last half century. The neutron production by proton accelerators was studied in USA in 1960s [1]. In 1970s, uranium targets were considered [2] for the FNAL Energy Doubler's 100 to 1000 GeV proton beams, and at JINR, Dubna [3] for a 660 MeV proton beam. Later, the process of energy production in heavy metal targets in fission sustained by spallation reactions induced by accelerated proton and ion beams was explored both theoretically [4] and experimentally [5, 6]. A number of experimental ([7, 8, 9, 10, 11]) and simulation ([12, 13, 14, 15, 16, 11]) studies have been undertaken employing heavy metal and fissile targets. As a result of many years of studies, the understanding has been reached [17] that cost-optimised industrial-scale Accelerator-Driven and Transmutation Systems (ADS) will require $1-2$ GeV beam energy, and tens of MW of continuous wave beam power producing thermal power in the GW range. Some of recent examples of ADS large-scale designs include Japanese (JAEA, 1.5 GeV, 30MW proton beam, 800 MW thermal power) [18], European (EFIT, 0.8 GeV, 16 MW proton beam) [19], and US-based (ATW, 1 GeV, 45 MW proton beam, 840 MW thermal power) [20]. This work was initiated in connection with recent considerations [21] of building an energy production and material testing station at FNAL Megawatt GeV-range proton beams.

2. Simulation

2.1. Models

In this paper, the simulation spanned the proton energy range 0.5 to 120 GeV and was performed on tungsten, thorium, and natural uranium targets using the MARS15 code ([22, 23]). The model used in this work is shown in Figure 1. It is a 60 cm in radius and 110 cm long cylindrical target with a 10-cm diameter, and a 35-cm long beam entrance channel. Target and hole dimensions were chosen to keep the neutron leakage at the level of a few percent in the entire energy range (Figure 2). The proton beam in the first simulation was uniform and parallel, 10 cm in diameter. After the optimal energy range had been determined, in the second simulation the beam of optimal energy was steered on the outer surface of the target model in order to minimize peak temperature. The choice of materials for the targets was determined by their properties as neutron producers in spallation (W, ^{232}Th) as well as their abundance and representativeness of heavy fissile material (^{nat}U). In the course of simulations, the built-in CEM and LAQGSM [24] event generators were invoked in MARS15 in order to determine outcomes of the hadron-nuclei interactions in the range (∼few MeV to 8 GeV, for negative pions from 0 to 8 GeV). Above 8 GeV, the MARS15 inclusive model was used for all nuclear interactions.

Radiation damage (expressed in the units of displacement-per-atom, DPA) depends on material composition and temperature, and is a strong function of projectile type, energy, and charge. The quantity is calculated in MARS15 as displacement of atoms from their equilibrium positions in crystalline lattice, and can lead to deterioration of materials' critical properties subsequent to their irradiation by high fluxes of particles. The calculation of DPA was performed on the targets in order to estimate their possible damage due to irradiation; in the case of use of the target as a Material Testing Station [21], creation of areas of high damage in targets is a goal.

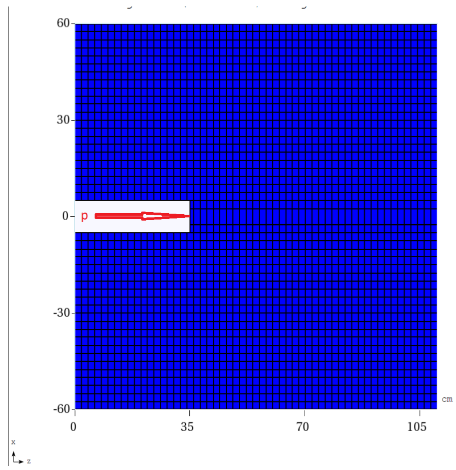

Figure 1: The MARS15 model of the ^{nat}U (W, Th) target.

All products of elastic, inelastic, and Coulomb elastic scattering of charged particles with energies above 1 keV contribute to DPA in the MARS15 built-in model. For neutrons both elastic and inelastic interactions are taken into account; for the neutrons below 150 MeV damage cross section is calculated using the NRT model [25] based on the cross section library FermiDPA 1.0 for 395 nuclides [26] created using the NJOY99 code [27].

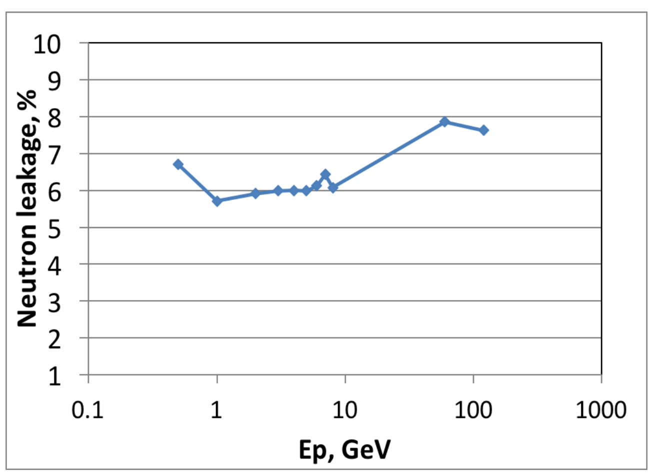

Figure 2: Neutron leakage from the surface of the ^{nat}U target

2.2. Neutron production and fission

Figure 3 gives the simulated number of neutrons generated in the target in all possible processes per incident proton and per GeV beam energy (the energy cost of neutrons) as a function of the proton energy. For all the three target materials these distributions show that the optimal energy for neutron production is between 2 and 4 GeV. The absolute number of fissions per GeV (Figure 4) is in agreement or slightly higher than in other studies for uranium [2, 4], and higher than for thorium [14]. Another difference is that many other studies report the optimal energy to be close to 1 GeV, while our simulations reveal the optimum at 2 - 4 GeV. This difference is most probably due to the fact that we use the latest version of LAQGSM generator for high-energy spallation which has recently been modified to incorporate a more detailed physics processes description [23] in the range 1 - 10 GeV based on a better adjustment of the model to available differential data. Most fissions in the uranium target

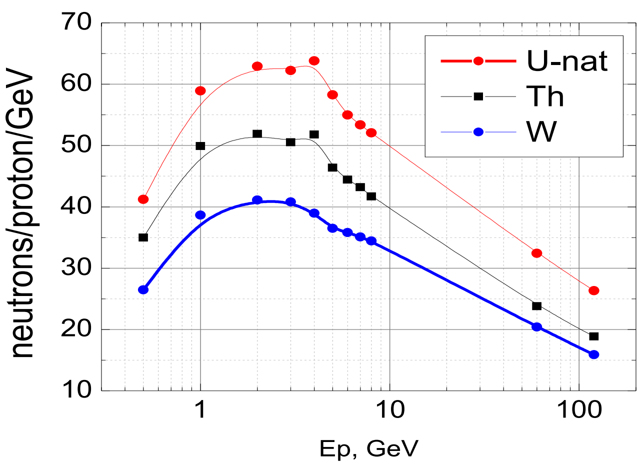

Figure 3: Number of neutrons released per one proton per GeV in the target.

(Figure 4) also occur in the above energy range, suggesting that a significant part of the neutrons are created in fission. In the case of the tungsten target the fission has peak at 1 GeV, but its contribution is smaller by three orders of magnitude. This explains the neutron surplus of 20 neutrons in the uranium target as compared to the tungsten one. Figure 4.

2.3. Energy production

Energy multiplication, which is defined as the ratio of the energy deposited in the target to that of the primary beam impinging on it, is shown in Figure 5. It has the peak in the same 1 - 4 GeV range as above for ^{nat}U and Th because the factor is >1 due to fission in the target. The fission cross section for tungsten is by orders of magnitude smaller than that for ^{nat}U. That is why the energy gain for tungsten is less than 1, and that material cannot serve efficiently for the

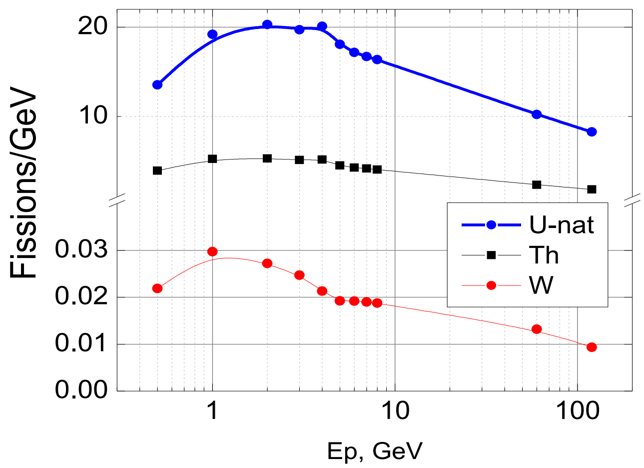

Figure 4: Number of fissions in the target per GeV proton energy.

energy production. The energy deposition in the thorium target is also much lower. Energy deposited in the target per neutron produced in it (Figure 6) is the quantity that shows the energy released relative to neutron production efficiency at particular beam energy. This quantity has a minimum between 2 and 4 GeV for both ^{nat}U and W; energy deposition in all processes in the target per one produced neutron is up to 6 times higher in the ^{nat}U target than in the W one. Note that for ^{nat}U, the differences between the values of this quantity at the optimal proton energy of 3 GeV and at minimal (0.5 GeV) and maximal (120 GeV) energies studied are about 15 %, making that difference not a very significant factor.

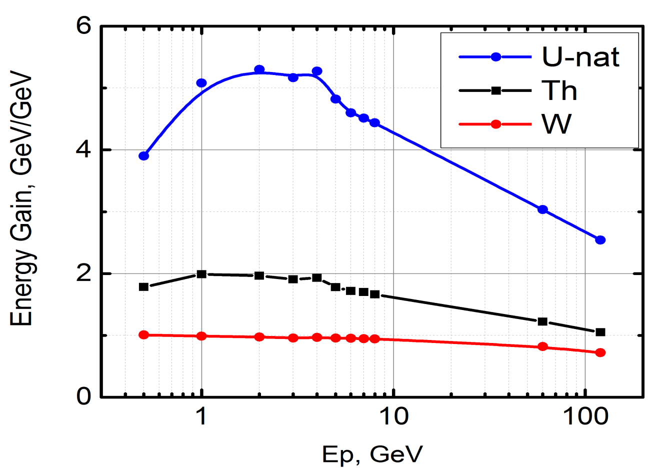

Figure 5: Energy multiplication in the targets.

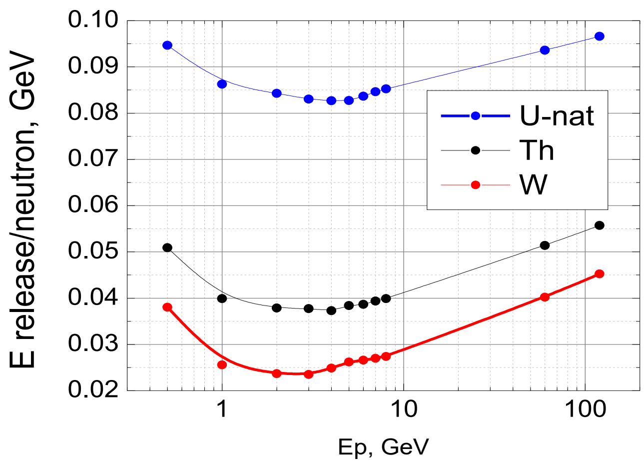

Figure 6: Energy released in the target per neutron and per GeV proton energy.

2.4. Radiation Damage and Gas Production in the Targets

The efficiency of the studied target as a Materials Test Station (MTS) is also evaluated here (see [21] for discussion of a liquid target concept proposed for that purpose). The aim of MTS is to maximize the DPA radiation damage as well as gas production in order to load the samples under study in the hottest location in the target. Figure 7 shows the target volume with DPA >20 yr^{-1} (at the beam intensity of $6.25 \cdot 10^{15}$ p/s), which is one of the reference numbers used to evaluate the MTS performance [21]. For both target materials such quantity has an maximum around 2 - 3 GeV.

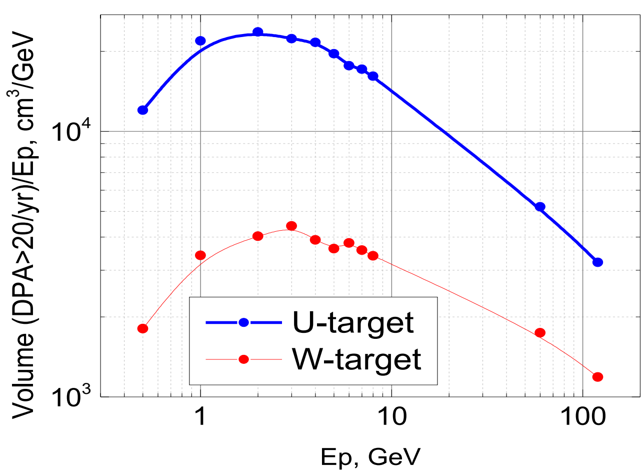

Figure 7: DPA volume in the targets.

The DPA volume shows the volume of the target which receives the DPA greater than 20 per year (that makes it usable for testing radiation hard materials, for example, for use in high-energy physics experiments). The choice of units (cm^3/GeV) allows to assess the cost of creating this DPA volume in terms of accelerated beam energy. Figure 7 indicates that the range 1 - 4 GeV, which has been shown to provide better energy gain and smallest neutron cost, is also optimal for the use of the targets as materials testing facility.

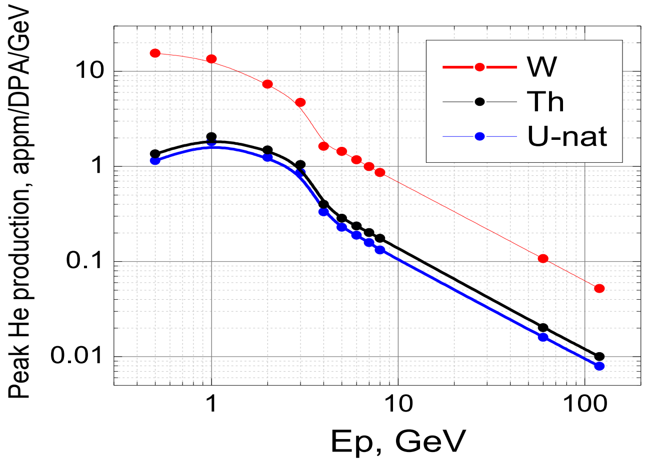

Figure 8: Helium ($_2He^4$ and $_2He^3$) production in the targets.

One of the key quantities to estimate radiation damage in a target or a reactor unit (in addition to DPA) is the peak helium production expressed in units of appm/DPA per GeV beam energy (see Figure 8). For U and Th, it has a maximum between 0.5 and 3 GeV; the helium production per unit energy grows faster than DPA up to 2 GeV and at higher energies its growth becomes slightly slower. The Figure indicates that the gas/damage/E_p ratio is highest (has the lowest cost) at lower energies between 0.5 and 4 GeV, while at 120 GeV it is two orders of magnitude less efficient. In absolute numbers, the helium production per DPA per E_p is a factor of 7 less for the ^{nat}U than for W target. For tungsten it is at the level of a typical fusion reactor and slightly less than for a spallation neutron source, like SINQ [28]. For the ^{nat}U target at 1 to 3 GeV it is at the level of a fission reactor on fast neutrons. The behavior of the curve in Figure 8 above 8 GeV remains the same even if the LAQGSM model is used in that range instead of the inclusive one, for example, the appm/DPA/GeV value at 120 GeV drops by 20% (this quantity represents a cost of the appm/DPA production; in appm/DPA units it grows with energy and saturates at high energies). Therefore, for the use as Material Testing Stations (MTS), Th and ^{nat}U targets are the most effective as high helium appm/DPA producers at 1 GeV, and W – below 1 GeV. However, it is important to mention that various designs of MTS can include such materials as steel or Zircalloy as components of the test matrix and their radiation damage and helium production need to be studied separately.

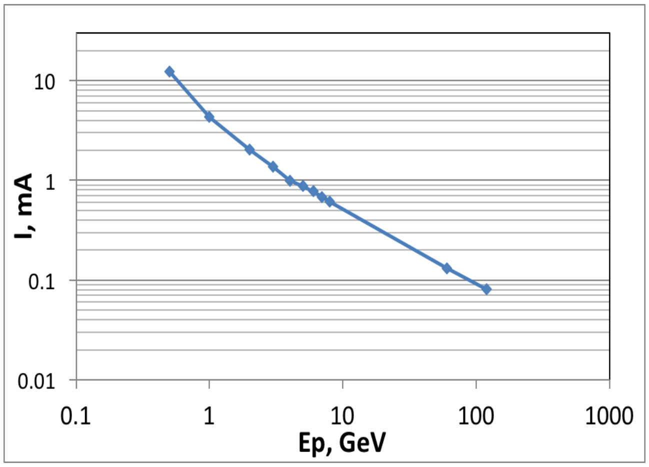

Figure 9: Proton beam current required for 1 GW output power for the ^{nat}U target.

2.5. Thermal output power

In order to use the target station in the energy production mode, so that the energy release in the target was higher than the energy used by accelerator, the following condition (1) (see, for example, [2] should be satisfied:

$$P = P_{rel} - P_0 - P_{acc} \leq 0 \tag{1}$$

where P is the potential power produced by the station, P_{rel} is the power released in the target, P_0 is the power needed to run accelerator in the idle mode, P_{acc} is the power fed to RF system to accelerate protons. It has been estimated [2] that the proton intensity required at the Tevatron energies was obtained taking P_0 to be 20 MW, and $P_{acc} = b \cdot I \cdot E$, where $b = 2$. It was assumed that P_{rel} is equal to $0.2 \cdot a \cdot I \cdot E$, where 0.2 is the energy released per fission in GeV, and $a \approx 60$ neutrons per fission, I is the proton beam current, and E is the proton energy. This latter is an estimate of the energy released in fission, assuming that neutron production is constant and each neutron is captured by uranium leading to the production of plutonium. A more detailed approach relevant to the accelerator-driven energy production calculations is described in [29]. In that approach, the thermal output power of an energy station can be described by the following equation :

$$P_0^{th} = I \cdot E_p \cdot G \tag{2}$$

where I is the proton beam current (mA), E_p is the proton beam energy (GeV), and G is the energy gain.

The energy gain (see Figure 10) is the key quantity, a high value of which in a system allows a significant increase in the output power as compared to the proton beam power provided that the target is capable of an efficient neutron

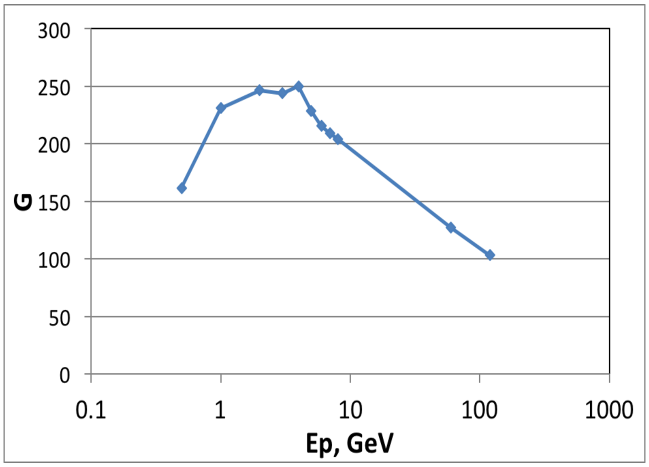

Figure 10: Energy gain G for the ^{nat}U target.

multiplication. The energy gain [29, 14] is described as follows:

$$G = \frac{\chi_s \cdot \phi^* \cdot k_{eff} \cdot E_f}{\nu \cdot (1 - k_{eff})} \tag{3}$$

where χ_s is the number of neutrons leaving the target and entering the blanket in target-blanket ADS. In our case the whole target (a full absorption target) serves as its own blanket and both the neutron multiplication and energy production take place in its entire media and that is why χ_s was taken to be equal to the number of neutrons produced per proton in the target (see Figure 3). The other quantities in the equation above were assumed to have the following values : $k_{eff} = 0.98$ (a typical number assumed for ADS), $\phi^* = 1$ (importance of the source of neutrons with respect to that of the fission neutrons, see [29] for details). This factor can be larger than 1 if other neutron sources than fission exist in the system; in our case a conservative assumption is made. The number of fissions per neutron ν was taken to be 2.5, and $E_f = 0.2$ GeV is the energy released per one fission.

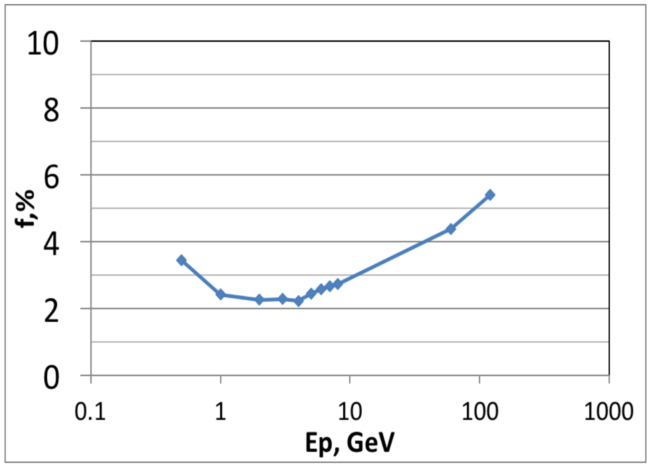

Figure 11: Fraction of the output power required to operate the accelerator for the ^{nat}U target.

Figure 9 gives the proton beam current required for the natural uranium target to produce 1 GW of thermal output power (1). It indicates that in the optimal energy range (assuming 4 GeV beam energy) one needs 1 mA of proton beam power to produce 1 GW output power; it requires more than 10 mA below 1 GeV, and it is at the level of 80μA for a 120-GeV beam. Another important quantity is the fraction of the thermal output power required to support the accelerator operation. It is defined [29] as:

$$f = \frac{1}{G \cdot \epsilon \cdot \eta}, \tag{4}$$

where ϵ is the electric to beam power conversion efficiency, 0.4, and η is the thermal to electric power conversion efficiency, 0.45. Figure 11 shows the f dependence on the beam energy. The optimal beam energy (defined by the energy gain G) is between 2 and 4 GeV.

2.6. Thermal analysis

A thermal analysis using the ANSYS code has been carried out in order to determine the feasibility of such a target from the point of view of the heat removal. The simplest cooling scheme with the cooling lines indicated by the orange color is shown in Figure 12.

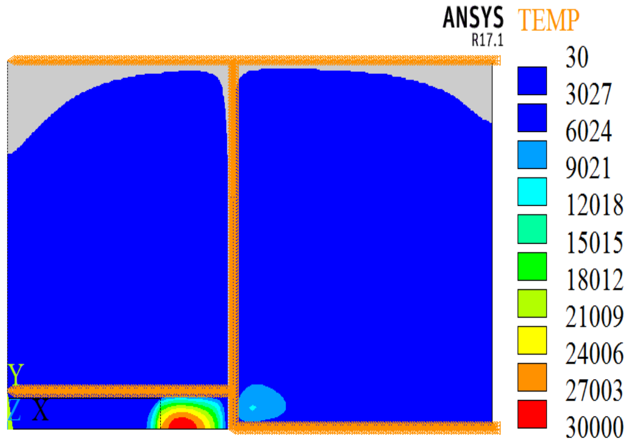

Figure 12: Temperature distribution in the ^{nat}U target after 100 s of irradiation with R= 5 cm beam with a simple water cooling line (shown in orange) scheme with $T = 20°$ C.

The heat map was calculated with MARS15 for a $E_p = 3$ GeV proton beam with the current $I_p = 0.5$ mA. The bunched beam was assumed to have the following parameters (similarly to those used in [21]): the bunch duration is $4 \cdot 10^{-11}$ s, the interval between bunches is $6.08 \cdot 10^{-8}$ s. The thermal analysis showed that during the first 100 s of irradiation, the target core will reach the temperature significantly higher than the melting temperature of natural uranium (1132.2°C). The hot spot is highly localized due to a small beam diameter (10 cm) as well as a low thermal conductivity of the natural uranium, 27.5 $W/(m \cdot K)$. Therefore, the use of the uranium target as a part Material Testing Station cannot be justified.

2.7. A target with the beam steered onto its surface

A possibility to use the target as an energy production station was also explored by steering the proton beam uniformly on the entire outer surface of the target (the beam is normal to the surface). Although this consideration is a necessary step to avoid the melting of the target, it is important to mention that neutronics and energy deposition of such target will be essentially different from the target considered in the previous sections. For the case of beam steering and it turns out that the energy multiplication at 3 GeV is ~ 4 (versus 15.5 in the version where the beam hits the center) while neutron leakage is $\sim 45\%$ of the total number of neutrons produced in the target. Thus, this scheme cannot be called a full absorption target. To account for that neutron, loss from the target when calculating the required beam current we additionally multiplied G by 0.55. As a result, the required beam current at 3 GeV is 2.8 mA (for 1 GW), i.e. at the level of $1 \div 2$ GeV, and the fraction needed to supply the accelerator is 4.6% (compared to 2.3% for the full absorption one). Thus, this fraction is largest in the range $0.5 \div 60$ GeV.

Under the aforementioned assumptions of beam energy and current, the power density map was simulated using the MARS15 code (Figure 13), and the ANSYS analysis performed to determine the target heating after 3 days of irradiation (Figure 14), and as a function of time (Figure 15). In this case, the maximum power density, as expected, is located at the depth of approximately one nuclear interaction length, and the volume beyond that maximum is less significantly irradiated (Figure 14). In order to minimize the target temperature down to below the melting point, an optimization study has been carried out.

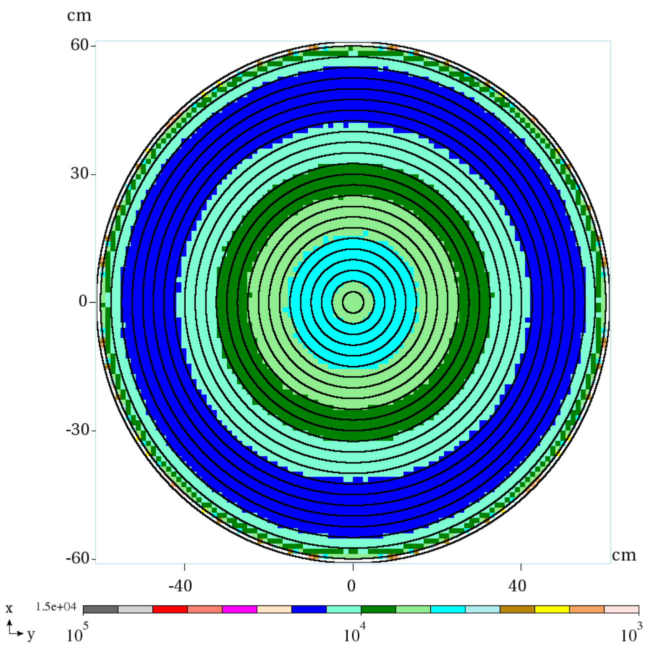

Figure 13: Power density map (mW/cm^3 of the ^{nat}U target irradiated by a 3-GeV 0.5-mA proton beam steered uniformly on the outer surface of the entire target.

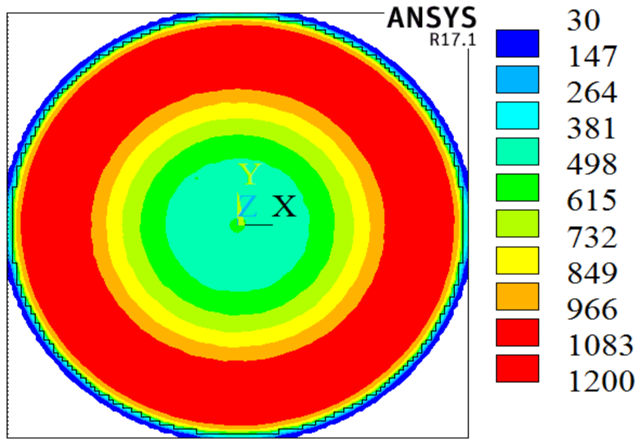

Figure 14: Temperature map of the target after 3 days of irradiation.

The study indicated that in order to attain the goal, the target has to be divided in smaller cylinders of length shorter than 13.75 cm. The outer surface of the cylindric target as well as the front and back planes of the smaller parts have to be cooled (presumably, by gaseous helium) down to the constant temperature of 25° C. The film coefficient (heat transfer coefficient) is assumed to be 5000 $W/(m^2 \cdot K)$. The Figure 15 shows that the peak temperature in the target saturates to ≈ 950°C in ≈ 30 s, and remains constant. This result suggests that assuming a design of the target involving splitting the 110-cm target in ∼ 13.5-cm-long cylindric pieces with a constant temperature of 25°C on all surfaces can allow to use it as an Energy Station at a ∼ 3-GeV 0.5-mA proton beam.

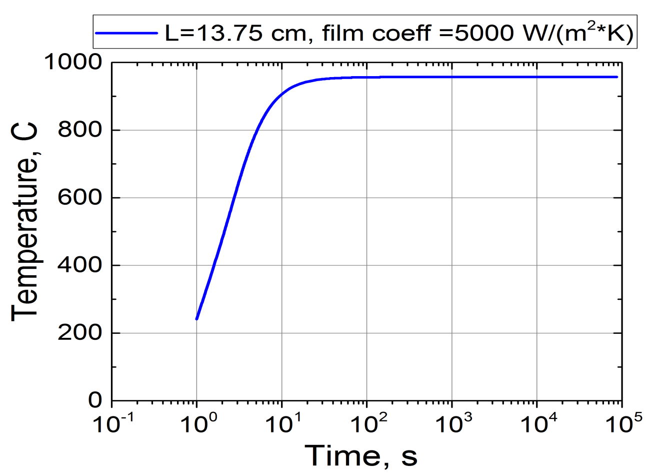

Figure 15: Peak temperature in the ^{nat}U target.

3. Conclusions

MARS15 simulations and ANSYS thermal studies of solid ^{nat}U, Th, and W full absorption targets as well as a ^{nat}U target with a beam uniformly steered on its surface have been performed. Target dimensions were optimized for the full absorption one to keep the neutron leakage below 8% of the total number of neutrons produced in the target in the 0.5 - 120 GeV energy range. The studies reveal that in order to maximize neutron production, energy deposition, energy gain, and radiation damage (DPA) volume, the optimal energy range is 2 to 4 GeV. For the optimal helium appm/DPA ratio (not including possible target components including lighter metals), the preferable energy is 1 GeV (for Th and ^{nat}U targets) and < 1 GeV for the W one.

It was shown that in the optimal energy range, the 1÷2-mA proton beam current can be sufficient to attain the 1-GW thermal output power in the case that the ^{nat}U target is used in the Energy Station. The fraction of the output power required to operate the accelerator in the entire energy range under scrutiny would not exceed 6%. Nevertheless, thermal analysis suggests that such design will not be feasible because of the target meltdown. Thermal analysis indicated that the irradiation of the ^{nat}U target core center by a $\sim$ 0.5-mA 3-GeV parallel proton beam will cause a core meltdown in seconds.

In the case that the beam is steered on the outer surface of the ^{nat}U target and the entire target is sectioned in $\sim$ 13.75-cm-long parts cooled, for example, by helium (a 25° C temperature is maintained on surfaces of each section), such solution can be promising (while probably technically difficult) for the target to serve an Energy Station in the studied proton energy range. In such case, the target cannot be deemed a full absorption one because the leakage of neutrons will be as large as 45%. Nevertheless, the calculations showed that it still looks attractive because in absolute numbers the fraction in not very large and the required beam power (2.8 mA under discussed assumptions) seems acceptable. However, technical feasibility of such scheme requires studies that go beyond the scope of this work.

References

[1] A. Weinberg, Proc. Int. Conf. Isochr. Cycl., Tennessee, USA, 1966.

[2] R.R. Wilson, Very Big Accelerators as Energy Producers, FERMILAB-FN-0298, 1976.

[3] R.G. Vassilkov et al., At. Energy, V. 44 (4), p.329, 1978.

[4] V.S. Barashenkov et al., At. Energy V. 37, p. 475, 1974. (In Russian)

[5] Fernandez, R., Mandrillon, P., Rubbia, C., Rubio, J.A., 1996. A Preliminary Estimate of the Economic Impact of the Energy Amplifier. Preprint. CERN/LHC/96-01-EET.

[6] D.L. Wang, China Nuclear Science Report (in Chinese) CNIC-00506 SINPC-0001 (1991).

[7] S. Andriamonje et al., Phys. Lett. B 348, pp. 697 - 709, 1995.

[8] R. Brandt et al., Rad. Meas. V. 31 (1), pp. 497 - 506, 1999.

[9] J. Adam et al., Appl. Rad. Isot. V. 107, pp. 225 - 233, 2016.

[10] W. Furman, J. Adam, L. Závorka, M. Suchopár, O. Svoboda, J. Vrzalová, V. Wagner, et al., "Recent results of the study of ADS with 500 kg natural uranium target assembly QUINTA irradiated by deuterons with energies from 1 to 8 GeV at JINR NUCLOTRON", Proceedings of Science (2012), Baldin ISHEPP XXI, 086.

[11] L. Zavorka et al., Annals of Nuclear Energy 80, pp. 178 – 187, 2015.

[12] R.R. Fullword, LANL Report LA-4789-UC, 1972.

[13] A.V.Dementyev at al., PSI-Proc. 95-02, Proc. ICANS-XIII 13th Meeting of the International Collaboration on Advanced Neutron Sources, October 11-14, 1995, Paul Scherrer Institute, 5232 Villiken PSI, Switzerland.

[14] S.R. Hashemi-Nezhad et al., Ann. Nucl. Ener. V. 38, pp. 1144 -- 1155, 2011.

[15] V.S. Pronskikh and N.V. Mokhov, Nuclear Data Sheets No. 120, pp. 222 – 225, 2014.

[16] Yu. Malyshkin et al., Nucl. Instr. Meth. in Phys. Res. B 334, pp. 8 – 17, 2014.

[17] H. Aït Abderrahim, J. Galambos, Y. Gohar, S. Henderson, G. Lawrence, T. McManamy, A. C. Mueller, S. Nagaitsev, J. Nolen, E. Pitcher, R. Rimmer, R. Sheffield, M. Todosow, Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production, FERMILAB-FN-0907-DI, 2010.

[18] H. Takano, R&D of ADS in Japan, Proc. OECD/NEA 4th Workshop on Reliability and Utilization of High Power Proton Accelerators, 2004, Daejeon, Korea.

[19] J-L. Biarrotte et. al., Accelerator R&D for the European ADS Demonstrator, Proc. 2009 Particle Accelerator Conference, TU2RAI02.

[20] G. Lawrence et. al., A Roadmap for Developing ATW Technology, LA-UR-99-3225.

[21] D. Wootan and D. Asner, PNNL Report PNNL 21134, February 2012.

[22] N.V. Mokhov et al., Fermilab Report Fermilab-FN-628 (1995); N.V. Mokhov et al., AIP Conf. Proc. 896, pp. 50–60 (2007); http://mars.fnal.gov.

[23] N.V. Mokhov et al., Progr. Nucl. Sci. Tech., vol. 4 (2014) pp. 496–501.

[24] S.G. Mashnik, K.K. Gudima, R.E. Prael, A.J. Sierk, M.I. Baznat, N.V. Mokhov, CEM03. 03 and LAQGSM03. 03 event generators for the MCNP6, MCNPX, and MARS15 transport codes, arXiv preprint arXiv:0805.0751, 2008.

[25] M.J. Norgett et al., Nucl. Eng. Des. 33, 50 (1975).

[26] V.S. Pronskikh, N.V. Mokhov, Fermilab Report Fermilab-FN-0960-APC (2013).

[27] R.E. MacFarlane et al., LANL Preprint LA-12740-M (1994).

[28] https://www.psi.ch/sinq/.

[29] M. Salvatores et al., Nucl. Sci. Eng. V. 126, pp. 333 - 340, 1997.

[30] H. Aït Abderrahim et al., Nucl. Phys. News, 20:1, p. 24 - 28, 2010.

[31] J.W. Weale, H. Goodfellow, M.H. McTaggart and M.L. Mullender, Measurements of the reaction rate distribution produced by a source of 14 MeV neutrons at the centre of a uranium metal pile, Journal of Nuclear Energy, Parts A&B, 14 (1961) 91.