CALCULATIONS OF TARGETS FOR ADS USING GEANT-4

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Abstract

Calculations of neutron production in metallic targets bombarded by protons with energies up to 1 GeV in framework of GEANT-4 are presented. Calculations of neutron production in targets of large size, dependencies of neutron yields on target dimensions and spatial distribution of energy deposited in the target, intended for working out ADS targets with multiplying blankets are also presented.

INTRODUCTION

Accelerator driven systems (ADS) as powerful spallation sources of neutrons can find their application in nuclear power engineering for transmutation of long-living radioactive waste, production of new elements and substances with fission capability and for power generation. In hybrid reactor also called energy amplifier (EA) - fission reaction takes place in sub-critical reactor while the necessary density of neutron flux is provided by the spallation neutron source.

Costs, dimensions and weights as well as power consumption of accelerators required in a large extend depend on the output power of EA. Installations with high (about 1GW) power output for their operation require beams of protons accelerated up to the energies of 1GeV and higher with intensities of hundreds of mA. Beams of charged particles with mentioned characteristics one can get only using unique expensive accelerator machines. However EA of 200-400MW output require substantially lower intensities of neutron sources. This fact allows one to make use of accelerators producing beams of several hundred MeV and few mA current which can be copiously produced by industrial means.

In our work on the basis of calculations performed within GEANT-4 framework (v.9.1) we present neutron yield for different metal targets (Cu,Fe,Ta,W, Pb) bombarded by proton beam with energies from 300 MeV up to 1 GeV and spatial distribution of heat deposited in target.

GEANT-4 (v.9.1) developed by CERN is a program package (a set of C++ libraries) designed for modelling particle interactions with matter on the Monte-Carlo basis [1]. GEANT-4 can be used with different types of projectiles, materials and geometry of targets (detectors) and user is free to choose models for physical processes involved according to the task, which he is working at.

In our calculations we take into account electromagnetic processes, i.e. multiple scatterings off nuclei and ionization losses of charged particles, together with nuclear processes. For modelling of high-energy hadron—nucleus interactions we choose Bertini intranuclear cascade model for the very first cascade stage of interaction (approx. 10^{-23} s). Excited nucleus formed after this first stage rather emits hadrons (cascade-exciton and evaporation models are used respectively for pre-equilibrium and equilibrium states of excited nucleus) or breaks up instantly (multifragmentation or Fermi break-up for light nuclei). Interaction of neutrons having energies lower than 20 MeV with matter is described by parameterization-driven models based on ENDF/B-IV neutron cross section libraries.

Interaction of particles with matter within GEANT-4 is modelled on step-by step basis, at each step characteristics of generated track can be extracted and processed. To obtain our results we process up to 10000 of primary proton tracks.

Computation error was determined according to root mean square deviation (RMS) of the quantity of interest, determined using same set of values for the quantity obtained by Monte-Carlo. That is, for N events and RMS value of D computation error on 3σ level for quantity X can be determined according to central limit theorem as

$$\Delta X = 3D/\sqrt{N} \qquad (1)$$

Table 1 represents comparison of experimental data on neutron yields from target bombarded by protons with GEANT-4 computations.

Table 1: Average Neutron Yield m from Cylindrical Lead Targets per 1 Proton

Target dimensions D×L cm	E_P, MeV	m, n/p GEANT-4	m, n/p experimental data	Reference (experimental data)
10.0×60	17	3.65±0.52	3.13±0.06	[2]
10.2×61	70	7.53±0.80	8.0±0.4	[3]
			6.4±0.3	[2]
	40	9.47 ±0.87	9.0	[4]
	20	14.99±1.02	11.8±0.6	[3]
			11.7±0.4	[2]
			13.3	[4]
	60	21.28±1.19	16.6±0.8	[3]
			16,8±0,5	[2]
			17.7	[4]
0.4×61	70	8.46±0.88	8.7±0.4	[5]
	20	16.24±1.14	13.9±0.7	[5]
	60	24.63±1.38	20.3±1.1	[5]

Comparison of GEANT-4 evolved quantities confirms a possibility to apply the toolkit for practical calculations of targets for ADS.

NEUTRON GENERATION IN TARGET

Neutron yield from the target depends on parameters of the charged particles beam, target composition and dimensions. Bombardment by high-energy particles produces a hadron-electromagnetic cascade in target matter. Accelerated primaries induce fission of atomic nuclei and creation of secondary particles which in their turn can also induce fission and create new generations of particles (protons, neutrons, mesons and γ-quanta). High-energy particles can induce fission not only of those nuclei for which fission can be induced by low-energy neutrons (e.g. uranium) but also of other heavy elements (e.g. tantalum, lead, tungsten). The latter ones can be used as the neutron-producing material of the target.

In Fig. 1 we present total number of neutrons produced in different metal targets as a function of the incident primary proton energy. Calculations are performed for infinite targets.

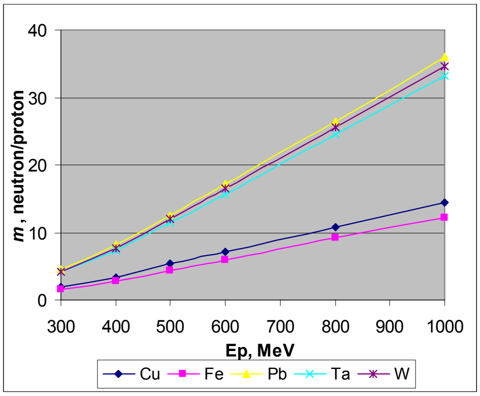

Figure 1: Total number of neutrons produced in infinite target.

Yields of neutrons (number of neurons which escape from the target) for finite targets depend on both beam characteristics and target dimensions. When dimensions are small a substantial part of secondary particles capable to induce fission with additional neutron production escapes form the target without interaction. At the same time in large target neutron radiative capture plays an important role.

For cylindrical target an optimal diameter with respect to neutron yield corresponds to few (2-3) characteristic inelastic interaction lengths λ_{in}. Due to anisotropy in particle production for inelastic proton scatterings in the lab frame (most of particles are produced in forward direction), the target length L should be somewhat larger than its radius, at the same time value of L has minor effect on the neutron multiplicity provided $L>D>\lambda_{in}$. Substantial part of neutrons escapes through the front butt-end of the target block, so neutron yield is maximal for comparatively small deepening of the beam injection point $z_0 \approx 0.3\lambda_{in}$.

In Table 2 we present calculated values for optimal dimensions of cylindrical target, Fig. 2 represents maximum neutron yields for them obtained via GEANT-4.

Table 2: Optimal Dimensions of Cylindrical Target

Material	D, sm	L,sm	Beam injection point, z_0 ,sm
Fe	40	50	5
Cu	30	50	5
Ta	20	50	2.5
W	20	50	2.5
Pb	40	50	7.5

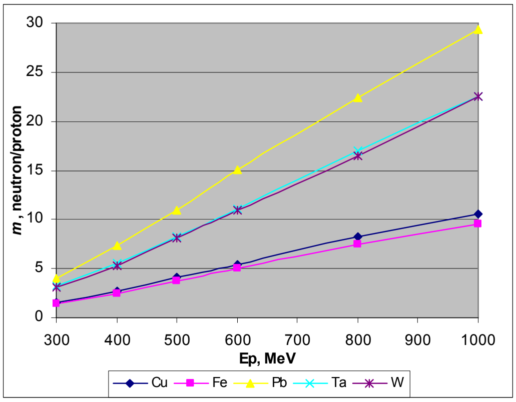

Figure 2: Maximal neutron yields for cylindrical targets. Target dimensions according to Table 2.

Energy spectrum of the neutrons obtained by electronuclear method is close to the fission spectrum. Specific energy spent for a single neutron production first drops with growth of beam energy E_p and stays approximately constant afterwards (see Fig. 3).

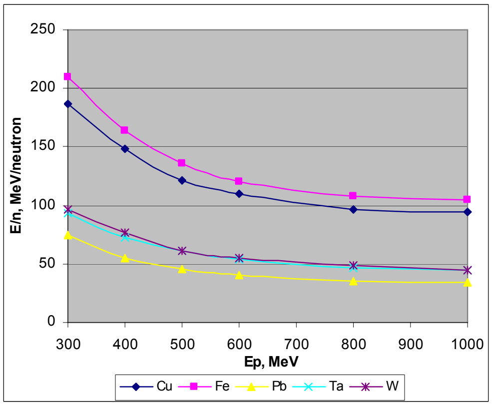

Figure.3: Specific energy spent for a single neutron yield. Target dimensions according to Table 2.

Power capacity of sub-critical reactor (N_T) with external neutron source spatial distribution similar to fission neutron one (reference external neutron source) is evaluated as

$$N_T = S_0 \cdot \frac{k_{eff}}{1-k_{eff}} \cdot \frac{1}{\nu} \cdot E_f \qquad (2)$$

where S_0- intensity of reference external neutron source, $k_{eff} < 1$ – multiplication factor, ν – mean number of neutrons per fission , E_f – energy released per fission.

From (2) it follows that for a subcritical reactor with 200 MW power output and k_{eff} =0.98 that ensures critical safety the needed intensity of the neutron source is S_0=4.2·10^{17}n/s. It is possible to reduce intensity of external neutron source locating one in the center of core and hence decrease neutron leakage. In case of cylindrical core the intensity of central neutron source (*S*) may be twice lower than reference source intensity (S_0).

Intensity of the electronuclear neutron source

$$S = \frac{I_p m_0}{e} \qquad (3)$$

with I_p standing for an average current of accelerator, m_0 – average neutron yield out of the target per single accelerated beam particle, *e* – charge of the accelerated particle.

Intensity S=2.1·10^{17}n/s can be reached for 5mA accelerator current if the yield is about m_0 = 6.5 neutrons per one primary accelerated particle. Our calculations (fig.2) show that the corresponding neutron yields can be reached for proton beam energies larger than 400 MeV for Pb target and larger than 450 MeV for Ta and W targets.

HEAT DEPOSITION IN TARGET

To determine temperature field in the target and for calculations of cooling system one should possess data on a heat deposition in target bombarded by charged particle beam. Heat deposition in target is due to ionization losses of charged particles, (electromagnetic interaction of charged particles with material), inelastic interaction of cascade hadrons (neutrons, protons, π-mesons) with nuclei of the target, fission of nuclei of target material.

Figure 4 represents results on relative heat deposition (ratio of total rate of heat deposition *Q* to beam power N_{beam}) in different materials (targets of optimal size w.r.t. the yield) at different proton beam energies.

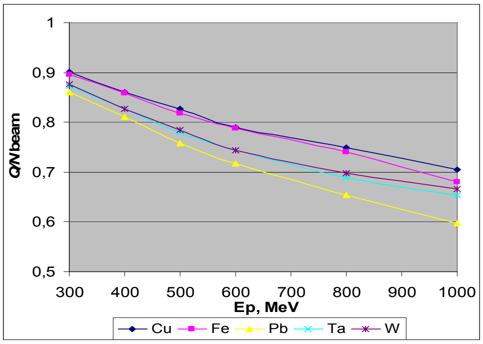

Figure 4: Relative total heat deposition in target.

Specific heat deposition is maximal along the beam injection axis. The maximum values of the specific heat deposition for a narrow beam are presented in Fig. 5.

In Fig. 6 we show calculated values for longitudinal heat deposition in copper target in comparison with experimental data [6]. The figure shows satisfactory correspondence of calculations with experiment.

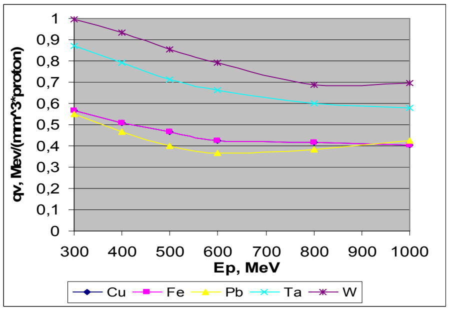

Figure 5: Maximal specific heat deposition for different targets.

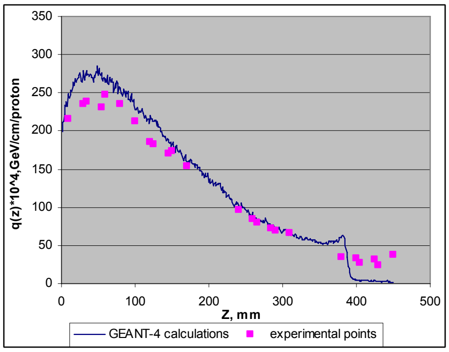

Figure 6: Longitudinal heat deposition in copper target. Proton energy 800 MeV.

CONCLUSION

1. Comparison of GEANT-4 calculations with experimental data confirms its applicability for ADS target calculation and design.
2. For EA with sub-critical reactor with power output of 200 MW at k_{eff} = 0.98 and 5mA accelerator current neutron yield should be as large as 6.5 neutrons/proton which can be achieved for heavy metal targets and beam energies slightly above 400-450 MeV.
3. For cylindrical targets optimal dimensions with respect to neutron yield are: diameter D=2...3 λ_{in} , length $L \approx D$, deepening of beam injection point $z_0 \approx 0.3\lambda_{in}$.
4. GEANT-4 gives a fair description of heat deposition in metal targets.

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