PROJECT OF A FAST NEUTRON TARGET BASED ON A 10 MEV 300 KW PROTON ACCELERATOR

M.S. Avilov, K.V. Gubin, N.Kh. Kot, P.V. Logatchev, P.V. Martyshkin, S.N. Morozov, S.V. Shiyankov, A.A. Starostenko, A. Andrighetto[1]*, Y.W. Bao*[1]*, L. Tecchio*[1]*, Ya.Z. Kandiev*[2]*, V.V. Plokhoi*[2]*, S.I. Samarin*[2]

Budker Institute of Nuclear Physics, 11, Ac. Lavrentiev Ave, Novosibirsk, 630090, Russia

[1]***Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare (LNL-INFN), Via Romea 4 - 35020 Legnaro (Padova) Italy***

[2]***Russian Federal Nuclear Center Russian Research Institute of Technical Physics, 13 Vasiliev St, Snezhinsk, 456770, Russia***

Project of targets for high intense neutron source is proposed. The source is based on a proton continuous accelerator with the 10 MeV particle energy and up to 300 kW mean beam power. Problems of fabrication of these targets are discussed. Hot solid state and liquid target designs are considered. Maximum admissible target parameters are presented. Advantages and disadvantages of various types of target for neutron production are discussed.

PACS numbers: 29.17.+w

1 INTRODUCTION

The low-energy proton beam of small transverse size (~ 1 cm) and high mean beam power causes a high density of energy deposition in a small volume of the target. The typical stopping length for protons of 10 MeV energy occurs to be less than 1 mm for some materials.

The main problem for target irradiated with the high-power beam is a heat removal from the active target area. This problem may be solved by the target surface extension for solid targets, or by use of liquid metal as a target operational substance. If the proton beam size can be increased in diameter up to 10 cm or more, it seems reasonable to use the stationary solid state target for neutron production. Otherwise, the rotated or liquid metal targets should be used.

Another serious problem is to choose the proper target material. The following materials have high neutron production ratio: ^{13}C, boron compounds, lithium, beryllium.

2 STATIONARY BERYLLIUM TARGET

When the proton beam size is rather large, the stationary beryllium target can be used for high neutron flux production. The layout of this target is presented in Fig. 1.

To avoid a target surface overheating, it is reasonable to produce the target of a conical shape that effectively extends its active area. This target is cooled by liquid agent, for example, water or liquid metal. In the latter case the size of the target should be essentially reduced. Parameters of the target cooled both by water and sodium - potassium alloy are presented in Table 1. The beam has a gaussian shape with σ_r=3.5 cm.

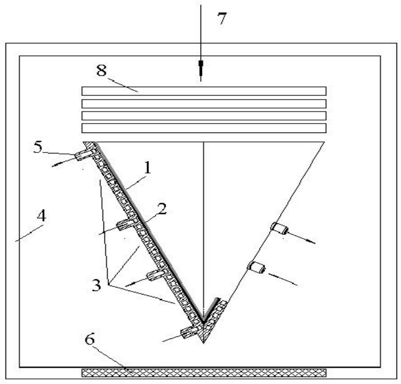

Fig. 1. Layout of the conical target with liquid agent cooling. 1 – operational layer, 2 – intermediate layer of liquid metal, 3 – conical backing with cooling channels, 4 – vacuum chamber, 5 – inlets and outlets of cooling channels, 6 – neutron beam output window, 7 – primary beam, 8 - collimator.

The intermediate layer of sodium-potassium alloy is used in order to decrease the thermo-mechanical stress in target elements. Maximum stress for the target cooled by water is $10.8\cdot10^7$ Pa, and maximum temperature of beryllium should be 200^{0}C.

Table 1. Parameters of the fixed beryllium target

	Water	Na – K alloy
Target length, m	0.9	0.4
Max. cone radius, m	0.06	0.06
Number of cooling channels	89	39
Coolant consumption, lpm	339	292
Max. coolant velocity, m/s	22	27

For the target cooled by the Na – K alloy the maximum stress is $25\cdot10^7$ Pa and maximum temperature of beryllium is 350ºC.

3 ROTATING TARGET

A serious drawback of the target presented above is its large size and, as a result, a low density of neutron flux. When the beam size is rather small, the rotating ^{13}C or boron compound based target seems to be the most attractive. These materials stand well the high temperature, and coolant is not required, since target cooling is carried out by thermal radiation.

The target layout is shown in Fig. 2. The target represents the rotating titanium disk with the diameter approximately 1-1.5 m. The disk rim is assembled from graphite or B_4C plates. Plate thickness is about 2 mm (stopping length of 10 MeV protons in graphite and boron carbide is about 0.7 mm), width – 1-2 cm, length – 10-12 cm. The disk is set on the shaft 5 cm in diameter.

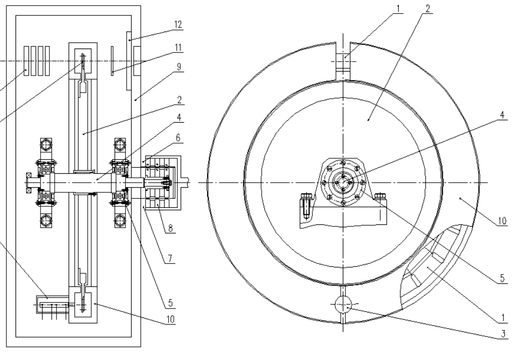

Fig. 2. Layout of rotating target.

Target rotation is carried out with a frequency of 30-50 Hz and transferred to the vacuum chamber via a magnetic clutch. The dissipation of heat is carried out in two water-cooled semi-circle aluminum channels. Channels have two gaps: operating one for incident beam, and technical one for temperature measurements (bolometer). A graphite collimator, which also acts as a beam position monitor, is placed opposite to the target. Behind the target the special graphite plate is placed for chamber protection and converter damage indication. The whole device is positioned inside the radiation shielding.

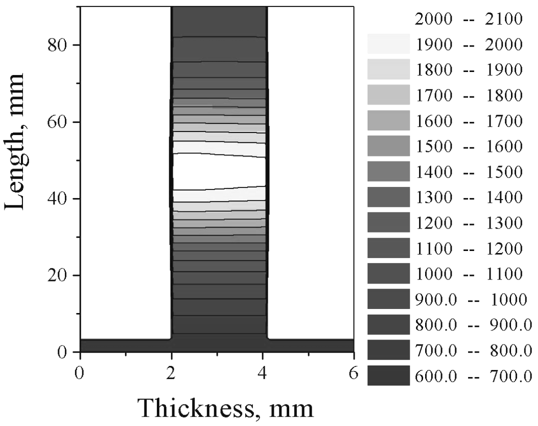

Fig. 3. Temperature distribution over the carbon plate irradiated by gaussian proton beam with σ =1 cm.

Result of simulation of temperature distribution over the MPG-class graphite plate irradiated by 300 kW gaussian proton beam is shown in Fig.3. The target diameter is 1 m. The front surface of the target is hotter than the rear one, and the highest temperature is observed near the point with maximum power deposition. Highest temperature does not exceed 2050^{0}C. The maximum termo-mechanical stress is about 10^7 Pa, that is 2 – 4 times less than the ultimate stress for graphite.

Another material suitable for intense neutron flux production is boron carbide. The production ratio for this material is higher than for carbon. Otherwise, the thermal conductivity of boron carbide is less than the one of carbon. As a result the temperature of the target hot area is 30% higher than for carbon target.

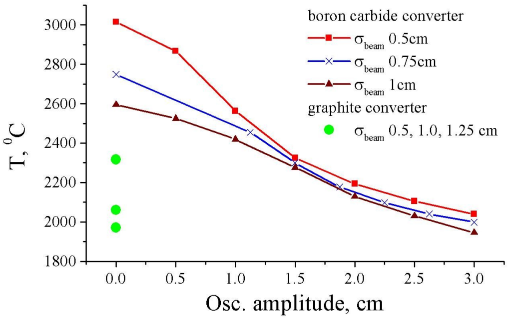

Fig. 4. Highest temperature of boron carbide and carbon targets for various beam sizes vs. cyclic motion amplitude.

The maximum temperature of boron carbide and carbon targets for various beam size is shown in Fig. 4. Points correspond to the maximum temperature of carbon target at a beam size of 0.5 cm, 1 cm, 1.25 cm (top to bottom). The most reliable temperature of the target seems to be 2000^O – 2100^{O}C. To decrease the temperature to this value, the effective target area has to be extended by the cyclic motion of the target axis in vertical direction. The acceptable temperature value is reached when the motion amplitude is 2.5 – 3 cm.

The maximum thermomechanical stress of boron carbide target is about 10^8 Pa that is 500 times less than its ultimate stress.

4 LIQUID METAL TARGET

The target where the hot area is removed from the active zone is based on the liquid lithium technology and usually represents a liquid lithium jet. Such a target requires large consumption of liquid lithium. In this paper the alternative type of target is proposed. Liquid lithium is contained in a special tank - liquid lithium container (LLC), its sketch is shown in Fig 5.

To avoid the local overheating, the liquid lithium has to be mixed up intensively. As a result, high-temperature liquid lithium layers are mixed up with low-temperature layers. The typical mixing size is approximately a few spot sizes of proton beam. By this way, the liquid lithium mean temperature is maintained fixed except the area, located directly under the proton beam.

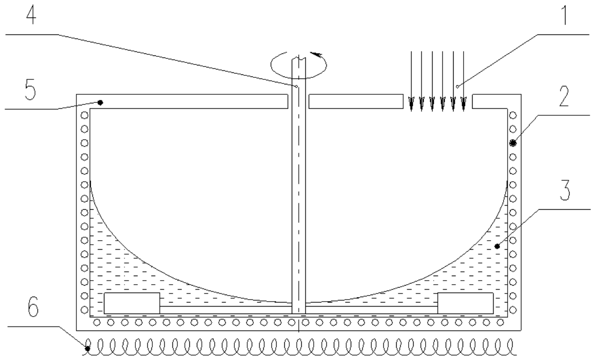

Fig. 5. Sketch of liquid lithium container. 1– incident proton beam, 2– cooling channels, 3 – liquid lithium, 4 – mixed-up device, 5 – container wall, 6 - preliminary heating device.

High melting point of lithium (190^{O}C) disables the use of water as a cooling agent, so liquid metals should be used as a heat carrier. After lithium is melted inside the tank, liquid metal should be loaded inside the cooling contour.

Liquid metal coolant selection is defined by its melting point. Melting temperature has to be as low as possible, not higher than 30 – 40^{O}C. Low melting temperature allows to decrease the mean operation temperature of liquid lithium, because the efficiency of LLC depends directly on the temperature difference between container wall and heat carrier. So, the higher the temperature difference is, the stronger the heat transfer should be. The mean lithium temperature should not exceed 300–350^{O}C, otherwise its strong evaporation takes place.

Since lithium is rather active chemical element, the corrosion resistance of material in liquid lithium environment strongly depends on admixtures content in it. Low carbon stainless steel stands well in liquid lithium environment and has rather high thermal conductivity (90 W/m·K against, for example, titanium, whose thermal conductivity does not exceed 20 W/m·K).

Only a few metals with a low melting temperature can be used as liquid metal heat carriers. Examples are sodium or potassium. These metals, however, have melting points around 100 ^{O}C. Sodium-potassium alloy, which is applied in nuclear reactors, has lower than pure sodium or potassium melting temperature - down to -12.5^{0}C. So, this material has been suggested to use as a liquid metal heat carrier.

Table 2. Main results of lithium container heat estimation

Cooling channel diameter	1 cm
Heat carrier speed	2.3 m/s
Maximum pressure differential in the channel	0.03 at
Total heat-carrier consumption	2.2 lps
Lithium mean temperature	230^{O}C
Container internal surface temperature	213^{O}C
Cooling channel wall temperature	184^{O}C
Heat carrier initial temperature	30^{O}C

The estimation of thermomechanical stress shows that the overheat of the container wall should not exceed 120^{O}C for steel as a wall material.

Main results of LLC heat estimation are presented in Table 2.

5 CONCLUSION

The advantages and disadvantages for each type of neutron production target are summarized in Table 3. Some of these items require additional study.

Various neutron target types may be used for various applications, for example, BNCT, radioactive ion beam production, material science application.

Table 3. Comparison of various target types.

Advantages	Disadvantages
Stationary beryllium target	
• absence of mechanical motion; • in the case of water cooling - no expensive materials; • ability to use a number of materials for neutron production.	• large source size; cooling channels are positioned so close to working area; • cooling agent is under the beam; • technology of working material deposition on the backing needs careful study.
Rotating carbon target	
• radiation as an intermediate heat carrier; • reliability and simplicity of design; • target destruction does not lead to disastrous effects for the accelerator; • material annealing at high temperatures eliminates radiation defects and reduces mechanical stress; • high rate of by-products diffusion from graphite at high temperatures; • the use of two rotating targets allows to reduce the thermal stress at small transverse beam size, and the length of carbon plates at large beam size.	• limited lifetime due to carbon evaporation; • high cost of material (^{13}C); • if use glassy carbon – complexity of plate treatment; • power extraction limit 200 W/cm^{2}, thus the maximum proton beam power should not exceed 300 kW; • target thickness grows with the beam energy raise.
Liquid Lithium Container	
• ability to receive the high power beam; • no beam energy limit; • low velocity of liquid metal heat carrier.	• Intense evaporation at temperature higher than 400 – 450 ^{O}C; • Careful control of lithium temperature is required; • Vertical or inclined proton beam.