TEMPERATURE AND OPTIMIZE DESIGN OF BEAM WINDOW IN THE ACCELERATOR DRIVEN SUB-CRITICAL SYSTEM*

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Abstract

Heat-transfer in the beam window is a critical problem in the design and operation of Accelerator Driven sub-critical System (ADS). Using the Monte-Carlo code Fluka, we studied the energy deposition of the beam window in high power proton of ADS accelerator and the corresponding temperature rising of the window with cooling. The temperature distribution of the beam window is calculated in presence of the coolant. The process of computation for various materials will be introduced, and an optimized design scheme is given. The results suggest that some measures could be used to reduce the damage to the beam window, such as dividing current into branch beams, enlarging the transverse beam size or using cermet as the material of the beam window, et al.

INTRODUCTION

In the ADS, chain reactions of fissile materials in sub-critical reactor are driven by neutrons generated from bombarding between the proto n beam and the spallation target. The ADS has advantages comparing with traditional critical reactors: 1) the available various fissile fuels since the Doppler effect does not seriously affect the systems' safety, 2) the acceptable small value of delayed neutron fraction since the margin to the prompt critical state can be kept by the sub-criticality. 3) ability to transmute the long-lived Minor Actinides (MA) from the traditional nuclear power generation. 4) suitable in many countries [1], and 5) much safe – the chain reactor will be terminated without the proton beam in case of the unpredicted power outage.

Due to high heat flux the beam window facing in the ADS, optimization design of beam window and an effective cooling system is important for long-lifetime and a security operation of the ADS system. In this paper we mainly focus on the temperature distribution of the beam window due to the high-power proton beam. In addition, we also compare the performance of the beam windows using various materials.

STRUCTURE OF THE ADS

The typical conceptual design of an ADS reactor contains an accelerator system, a neutron source and a sub-critical core. After accelerated by the linear accelerator, the high-power proton beam, guided by the vacuum chamber, will hit the spallation target. The lead-bismuth eutectic (LBE) is chosen as a spallation target as well as coolant, since it has a high neutron production rate, an effective heat dissipation and a very small amount of radiation damage properties [2].

As shown in Fig. 1, the beam window, a hemisphere locating at the outlet of the vacuum chamber, which separates the vacuum chamber from the spallation target, and prevents the radiation damage from the core.

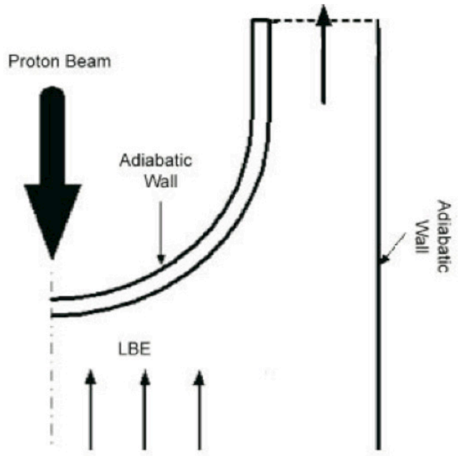

Figure 1: Structure of the beam window.

ENERGY DENSITY DEPOSITION EMULATION BY FLUKA

The proton beam energy deposited in the beam window (denoted by E_d) with different material are simulated by Fluka, where it assumes a high-power proton beam with energy of 1.1 GeV, average current of 3 mA and average power of 3.3MW. The results are listed in Table 1.

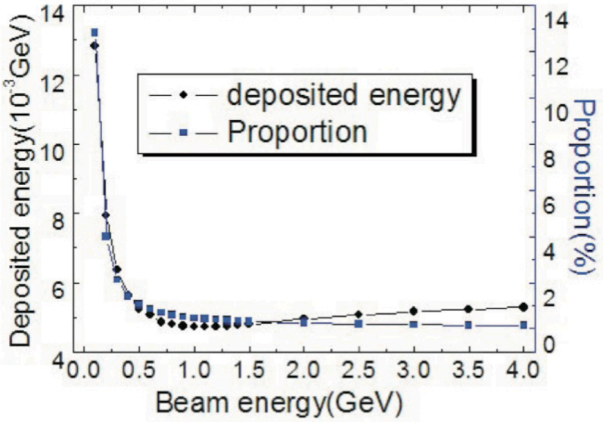

Figure 2: The black square line is correlation between energy deposition (per proton) and proton beam energy, and the blue square line is energy deposition shown as the fraction of the injected proton beam energy.

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Table 1: The Amount of Deposited Energy (E_d) Corresponding to Various Metals

Material	Density (g/cm^3)	E_d (10^3W)	Proportion (%)	Material	Density (g/cm^3)	E_d (10^3W)	Proportion (%)
Sodium	0.97	1.7269	0.0523	Nickel	8.90	16.4208	0.4976
Magnesium	1.74	3.2835	0.0995	Copper	8.96	15.4605	0.4685
Beryllium	1.85	3.2967	0.0999	Silver	10.5	17.2359	0.5223
Aluminum	2.70	4.9995	0.1515	Tantalum	16.65	24.7236	0.7492
Titanium	4.54	7.7946	0.2362	Tungsten	19.30	29.3436	0.8892
Iron	7.87	13.9854	0.4238	Gold	19.32	29.5878	0.8966

As indicated in the Table 1, E_d is increasing with the high density material. This can be attributed to the large size atom, which is thought as the most important factor related to the process and large material density.

In addition, E_d is proportional to the thickness of the iron beam window as given in Table 2. Furthermore, the correlation between E_d and proton beam energy is also studied with Fluka. The results are shown with the solid black square line in Fig. 2. The low energy protons will deposit much more energy on the window than that for the high energy ones. It is because that the low energy protons are easier to be trapped by the beam window. Due to the large speed of the high energy protons will have a large energy-loss during the collisions with the beam window. And the energy deposition shows a slow increase for protons with beam energy above 1.0 GeV.

Reading in Fig. 2 (solid blue square), one can see that the low energy protons will deposit 13% of its energy when passing by the window. However, the energy protons should be chosen to drive ADS as their less energy loss. However, the optimum proton beam energy for ADS is as low as 1.1 GeV, because of very high neutron yield at this energy.

PARAMETERS OF THE BEAM WINDOW WITH A COOLING SYSTEM

The small transverse size high-power proton beam will naturally deposit its energy in a very small area of the beam window. As the above discussion, the appropriate cooling is significant important in the ADS system. Liquid LBE is chosen as the coolant in our calculation, which has 44.5% lead and 55.5% bismuth [2]. The parameters of the liquid LBE and the proton beam are, respectively, listed in Table 3 [3] and Table 4 [4], where it has a round beam with the radius of 1 cm.

Table 2: The Value of E_d Corresponding to Iron Beam Window of Different Thickness

Thickness (cm)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	**1.0**
E_d (10^3W)	4.337	9.171	13.984	19.459	24.664	30.296	36.051	41.882	47.066	54.314

Table 3: Parameters of LBE (723K) [3]

Density (g/cm^3)	10.2
Thermal conductivity (W/m·K)	14.2
Thermal expansion coefficient (K^{-1})	1.2×10^{-4}
Dynamic viscosity (kg/m·s)	1.3783×10^{-4}

Table 4: Parameters of Proton Accelerator, Beam Window and Coolant

Accelerator		Beam window		Coolant [4]	
Beam current	3mA	Thickness	3mm	Material	LBE
Beam energy	1.1GeV			Flow rate	1.95m/s
Power	3.3MW	Material	Beryllium, iron or cermet	Inlet temperature	573K
Transverse beam size	1cm				

TEMPERATURE RISING OF THE BEAM WINDOW WITH A COOLING SYSTEM

The temperature relationship of the beam window and the massive cooling liquid can be written as [5]:

$$q_{\mathrm{v}} = \frac{E_d}{\pi R^2 d}, \qquad (1)$$

$$\begin{aligned} t_{\mathrm{f}} - t_0 &= q_{\mathrm{v}} d\left(\frac{d}{2\lambda_{\mathrm{u}}} + \frac{1}{h}\right) \\ Nu &= \frac{hD_{\mathrm{e}}}{\lambda} \\ Nu &= 5.0 + 0.025 P_{\mathrm{e}}^{0.8} \\ P_{\mathrm{e}} &= \frac{\rho u D_{\mathrm{e}} C_{\mathrm{p}}}{\lambda} \end{aligned}, \qquad (2)$$

where t_{f} is the temperature of the inner face of beam window; t_0 is the inlet temperature of coolant; q_{v} is the power of unit volume on beam window; d is the thickness of beam window; R is transverse beam size; λ_{u} is the thermal conductivity of beam window; h is the heat-transfer coefficient, in unit of $\mathrm{W/(m^2 \cdot K)}$; u is the flow rate of LBE; D_{e} is the diameter of coolant passage; ρ is the density of LBE; C_{p} is the heat capacity; λ is the thermal conductivity of LBE; P_{e} is the Berkeley number. The parameters can be found in Table 3 and Table 4.

In our computation, three types of materials, iron, beryllium and cermet, are considered. For Iron, E_{d} is 1.4×10^4 W, and then from Eq. (1) and Eq. (2), it can be calculated that q_{v} is $1.484\times10^{10}\ \mathrm{W/m^3}$, and t_{f} is 8620 K, under which the Iron window will be gasified. For Beryllium, q_{v} is $3.498\times10^9\ \mathrm{W/m^3}$ and t_{f} is 2347 K, in that case, Beryllium will be liquefied. For cermet, because of its low density (about 2.7 $\mathrm{g/cm^3}$), E_{d} is reduced to 5×10^3W, and the results show t_{f} is 5100 K, which is lower than the melting point of cermet (about 6000 K).

As shown in Eq. (2), over-heating is mainly due to large q_{v}. So reducing q_{v} may be an effective way to slower the temperature rising. In fact, q_{v}, defined by Eq. (1), is almost independent of d because the direct proportional relationship between d and E_{d}, as can be seen in Table 2. So enlarging the value of R can reduce q_{v} effectively. According to our preliminary computation, a proton beam with R larger than 3.4 cm is required for Iron window to withstand the deposition power, while for the Beryllium window, 1.6 cm is enough.

In another way, we can extract the high power proton beam through several beamlines to the target [6], so that the heat flux on each beam window can be reduced. For example, 10 currents for Iron window and 3 currents for Beryllium window, can avoid the over-heating of the beam window.

CONCLUSION

The properly chosen material as well as the beam with optimum transverse size is important in design of the beam window. Using a mutli-beam is also a possible method to avoid the over-heating of beam windows.

Our preliminary results show that the performance of cermet window is better than that made of metal in many ways, so the cermet would be a promising material in the design of beam window.

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