THE DESIGN AND SIMULATION OF THE SAFETY PART OF THE EXTRACTION SYSTEM OF THE HEAVY ION CYCLOTRON DC280 USING COMSOL MULTIPHYSICS

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This paper presents the design and thermal analysis using COMSOL Multiphysics® of safety part of the extraction system of the heavy ion cyclotron DC280. The heavy ion cyclotron DC280 was developed and is being constructed at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. High thermal power of the extracted beam is a risk of destruction for the elements of the beam extraction system. The beam power is expected to be about 2.5-3 kW and the beam diameter is about 10 mm. The proposed model analyses mainly the temperature on the exposed by the beam area of the windows, contact temperature between the windows made of molybdenum and the body made of cooper, and temperature on the wall of the cooling channel. The article also discusses possibility of design for experimental verification. The results based on thermal analysis will give us a possibility to choose an appropriate configuration for its experimental verification on the stand.

KEYWORDS
thermal analysis, cyclotron, beam extraction system, COMSOL Multiphysics

1. INTRODUCTION

The heavy ion cyclotron DC280 is being developed and constructed at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research to increase the capabilities and efficiency of the experiments on the synthesis of the super heavy elements and to study their nuclear physical and chemical properties. The DC280 heavy ion cyclotron will produce the accelerated beams of ions with A/Z from 4 to 7 and mass number from 20 to 238, i.e., from neon to uranium. The DC-280 is shown in Fig.1. The energy of the accelerated beams will reach 4–8 MeV/nucleon, with the projected intensity >10 pμA for all ions with a mass number below 50. Thus, the modernization of the existing accelerators (U400, U400M) and construction of the new cyclic accelerator will create a possibility for conducting experiments with accelerated ions from deuterium to uranium in a broad energy range. Realization of the research program of the Flerov Laboratory of Nuclear Reactions for the period 2010–2016, based on the accelerator complex "Dubna Radioactive Ion Beams" (DRIBs-III), will allow the Laboratory to widen the spectrum of the research topics to be addressed and to synthesize new superheavy elements. It will also enable JINR to keep its leading position in nuclear research with heavy ions of low and intermediate energies in the nearest 25–30 years [Gulbekyan 2010].

The high thermal power of the extracted beam is a risk of the destruction (melting) for the elements of the beam extraction system, the diagnostic system and the beam line. The beam power is expected to be about 2.5-3 kW and the beam diameter is about 10 mm, it is represents more than 35 MW/m^2.

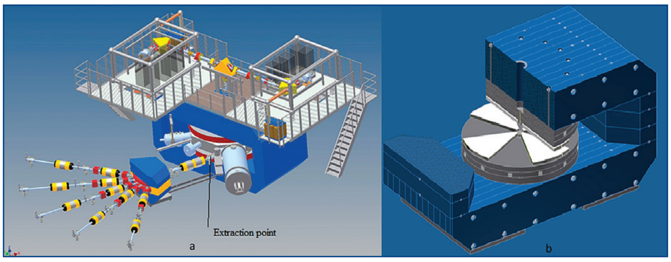

Fig. 1. a) The schematic diagram of the DC-280 cyclotron b) the electromagnet of the DC280 cyclotron

The extraction system includes the electrostatic deflector and the magnetic channel. The deflector is composed of two parallel plates ("septum" and "potential" plates). The electric field is created between the plates and deflects the ion beam from the cyclotron chamber to the magnetic channel than to the beam line. The deployment of the extraction system and other parts of accelerator system are shown by Fig. 1 and Fig. 2. A typical beam trajectory is also shown in Fig. 2 [Gulbekyan 2010].

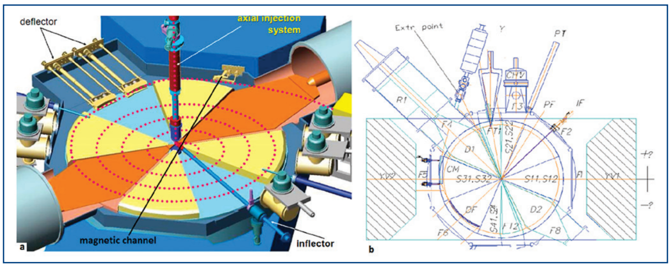

Fig. 2. a) The scheme of a typical magnetic structure and an accelerator system of the heavy ion cyclotron b) the schematic diagram of the accelerator system of the heavy ion cyclotron DC-280, CM-magnetic channel, DF-deflector

The magnetic channel is used for compensation the influence of the edge magnetic field of the cyclotron. The channel is situated between the sectors in vacuum chamber (expected pressure $< 10^{-7}$ [Torr]. The magnetic channel represents a set of steel elements in an external magnetic field which forms the required magnetic field shape for horizontal beam focusing. The assembly of magnetic channel is shown in Fig. 3. The main parts of the assembly are the vacuum flange, the magnetic channel, the linear actuators for positioning, the water cooling pipes and the supports constructions [Karamysheva 2010].

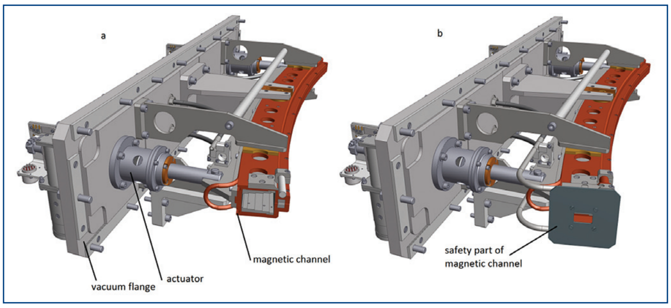

Fig. 3. The assembly of the magnetic channel of the heavy ion cyclotron DC-280 a) without the safety part b) with the safety part

2. DESIGN AND REQUIREMENTS

As written above, the safety part protects other parts of assembly before damage. The 8 MeV heavy ion beam, which irradiates the windows surface in a direction perpendicular to the surface, travels through the safety part materials where its energy is deposited by the interacting with ions. The heat generated in materials is then conducted to the surface where it is transferred to the cooling water by construction material and removed finally.

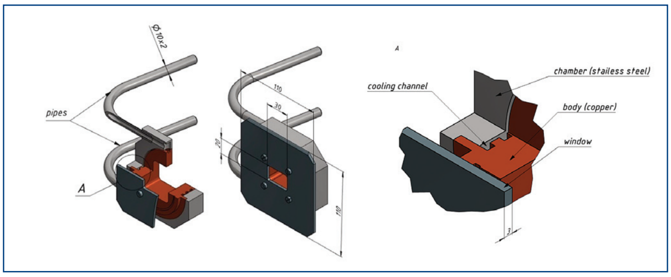

Fig. 4. Schematic diagram of the safety part (dimensions in millimetres)

The proposed model analyses mainly the temperature field as well as the maximum heat power of the ion beam which is able to withstand the existing configuration. The thermal model is focused on investigation temperature on the exposed by the beam area of the windows, contact temperature between the windows made of molybdenum and the body made of cooper, and temperature on the wall of the cooling channel. The detail design of the magnetic channel has drawn up by the staff of the Design Department of FLNR and basic dimensions of it are shown in Fig. 4.

During designing, designers have to be taken into consideration requirements such as a compact dimension, a material suitable for vacuum, cooling. The chosen material and its properties are given in the Tab.1. Because, the safety part is located into the vacuum volume (< 10^{-7} Torr), it is necessary to take into account the vapour pressure of the structural materials for proper function. Excess temperature at a given by vapour pressure cause evaporating a material, and it causes rapid decreasing of the vacuum. The material properties are shown in following table

Material/part	Melting temperature [K]	Max.temperature [K] for pressure ~ 10e⁻⁷ [Torr]	Thermal conductivity [W/mK]	Surface emissivity [-]
Molybdenum "windows"	2890	1960	138	0.05-0.18
Cooper "body"	1357	1060	389	0.072
Stainless Steel "chamber"	1809	1230	40	0.6

Tab. 1. Material properties [3]

3. THERMAL MODEL

In this study, the COMSOL Multiphysics 4.3 [User's Guide 2012] program was used to estimate the heat transfer in the safety part during the heavy ion beam irradiation. A model of the safety part configuration is divided into a number of small elements, usually with a brick shape defined as nodes in three dimensions. The temperature at each node is then calculated, taking into account the thermal conductivity of the material and the thermal boundary conditions (heat regions and cooled surfaces) imposed on the construction. A high level of accuracy in the calculations is achieved by choosing a large enough number of elements to model the safety part configuration. The overall accuracy of the analysis ultimately depends on how well the input parameters can be determined. In this work, combinations of conductive and radiation to ambient problems cannot be solved analytically, so numerical methods based on the Finite Element Analysis (FEA) code were employed [Lepers 2010]. In chapter 3.1 is described parametric calculation. In steady state regime thermal model is described by the following static heat conduction equation [User's Guide 2012]:

$$\nabla \cdot (k \nabla T) = 0 \tag{1}$$

$$-n \cdot (-k \nabla T)\big| = \frac{q_{tot}}{A} \tag{2}$$

$$-n \cdot (-k \nabla T)\big| = \varepsilon\sigma\left(T_{amb}^{4} - T^{4}\right) \tag{3}$$

Fig. 5 shows which the boundary conditions are applied to the surface. The chamber made of stainless steel Fig. 4 and Fig. 6 is neglected in thermal model, because it thermal conductivity is 10 times lowers than has cooper. On the surface 1 is applied the heat flux by the boundary condition equation (2). The surface to ambient radiation is applied to all surfaces of molybdenum window equation (3). The author expected temperature greater than 1000 K.

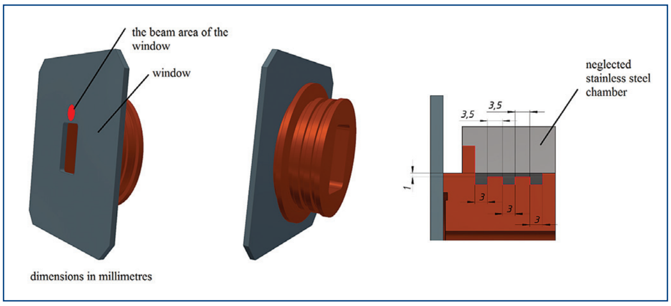

Fig. 5. Schematic diagram of the boundary condition deployment

On the water cooling channel (surface 3 in Fig. 6) is applied the convective cooling boundary conditions, it is described by equation (4).

$$-n \cdot (-k \nabla T)\big| = HTC\left(T_{ext} - T\right) \tag{4}$$

The average heat transfer coefficient HTC is calculation analytically by the following Dittus-Boelter equation:

$$HTC = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.4}\,\frac{k}{d} \tag{5}$$

The calculated HTC is about 6000 [W/m^{2}K], for water flow 2.5 [l/m], inlet water temperatures is ~ 20 [°C], author expected maximum temperature different 8 [°C] and pressure in the water cooling system 3–5 [bar(g)]. Thermal contact resistant is represented by the thin layer resistant boundary condition. It is considered as a thin (two case 0.1 mm and 24 mm) layer of gallium (40 [W/mK]). The thin 0.1 mm represents really gallium layer which the designers assume for batter thermal contact and 24 mm layer (equivalent gallium layer) which simulates simply contact between the molybdenum window and cooper body connected only by the four tantalum bolts M4 [Persov 2006].

3.1 The parametric sweep

The parametric sweep is used for the proposed thermal model and results are shown the temperature as function of parameter [User's Guide 2012]. The thermal model has calculated for all combination of value from parameter value list in Tab.2.

Parameter	Description		Parameter Value list		
W_beam	Heat power of beam	[W]	500	1500	2500
ds123	Equivalent thickness of contact resistance	[mm]	0,1	24	–
HTC	Heat Transfer Coefficient	[W/m²K]	2000	5000	8000

Tab. 2. Parametric sweep value list

4. RESULTS

This section presents the detail and result of calculation of the maximum and average temperature of the window, the maximum and average temperature on the cooling channel wall and finally the contact temperature between window and body.

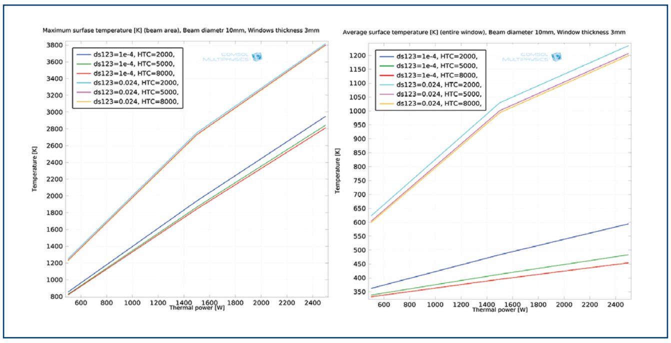

Fig. 6. The maximum and average temperature on the molybdenum window along beam power and sweep parameter

The graph on left in Fig. 6 shows that a crucial influence on the maximum temperature window has the effect of thermal contact, as shown in Tab. 1 a molybdenum can be used for a given pressure (10^{-7} [Torr]) at temperatures 1960K and together with prerequisite to using thin gallium layer (parameter ds 123 = 0.1 [mm]), the construction will be able to cool the beam heat power about 1 500 [W]. When considering contact with ds 123 = 24 mm can be a maximum output power of about 800 [W]. The right diagram on Fig. 6 shows the average temperature of the windows which suggests that in poor contact will prevail cooling of radiation to the ambient. The following Fig. 7 presents temperature distribution for the anticipated operating parameters. Fig. 6 shows that the HTC has insignificant influence on the maximum and average temperature of the window.

From the other side the HTC has significant influence on the maximum and average temperature on the cooling channel wall. As shown in Fig. 8 and Fig. 9. There is a risk of boiling on the wall. The minimum critical heat flux (CHF) for subcooled forced convection boiling, is in this situation 5.2 [MW/m^2] by the Gunter correlation [Gunther 1951]. In this case the maximum cooling channel temperature is 660K and saturation temperature of water is 394K that means the maximum temperature different 266K. The maximum heat flux in this study is ~ 0.6 [MW/m^2]. It is significantly smaller heat flux than CHF.

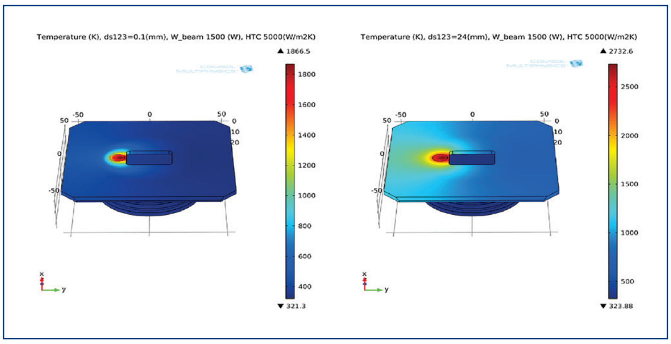

Fig. 7. Simulation result for the temperature field in two different thickness of alternative thermal resistant

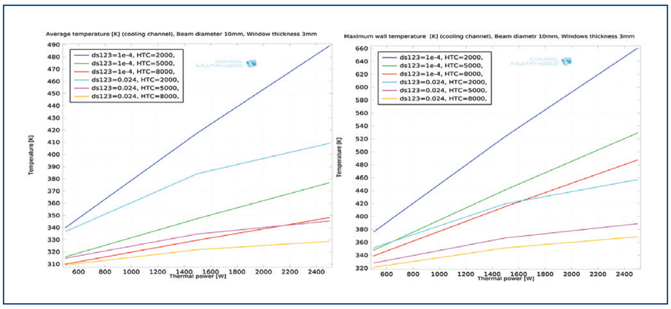

Fig. 8. The maximum and average temperature on the wall of cooling channel along beam power and sweep parameter

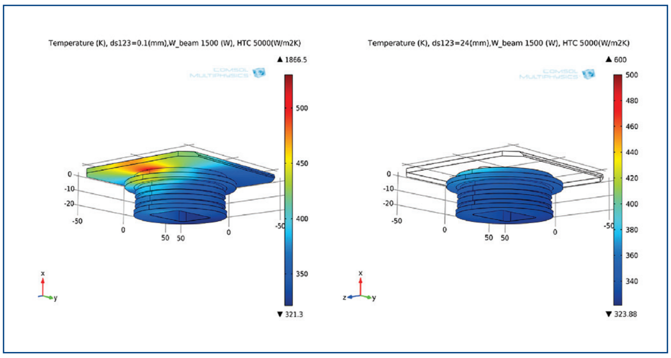

Fig. 9. Simulation result for the temperature field in two different thickness of alternative thermal resistant

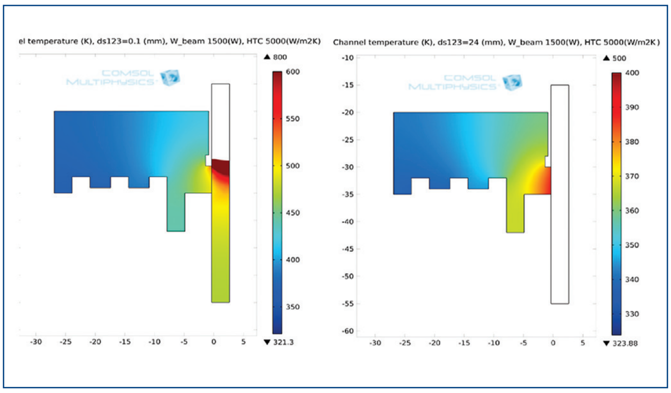

Fig. 10. Simulation result for the temperature field on the cooling channel wall and the contact area

Fig. 10 shown the temperature field in contact between window and cooper body as well as temperature profil in section view by plane xz. The diagrams show that temperature of cooper body in contact area is a margin below the melting temperature of copper.

5. CONCLUSION

Computational models have been developed for the design of safety part of the extraction system of the heavy ion cyclotron DC-280. Result from the computational models will be compared with experiment results. Experiment setup is currently under construction. It will be use the research infrastructures in Faculty of Mechanical Engineering, Brno University of Technology. Exactly EB Machine K26, which includes electron gun, beam energy approximately 140 KeV as well Thermal Imaging Camera, these infrastructures will be used for validation of thermal analysis and design of the safety part of the extraction system of the new built heavy ion cyclotron DC280 in FLNR. After evaluation of results of calculation and experiment it will be known behaviour of safety part and will take appropriate precautions for safe operation of the heavy ion cyclotron DC280.

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