

PAPER • OPEN ACCESS

## Selection of rotating entrance window and target parameters for a gas-filled separator operating at high intensive heavy ion beams

To cite this article: D Ibadullayev 2019 *J. Phys.: Conf. Ser.* **1390** 012003

View the [article online](#) for updates and enhancements.

You may also like

- [The effect of photomultiplier tube glass entrance window on plastic scintillator cast sheet photon dosimetry: A Monte Carlo study](#)  
N S Mohamed, A Aydn and S M Tajudin
- [Lateral response heterogeneity of Bragg peak ionization chambers for narrow-beam photon and proton dosimetry](#)  
Peter Kuess, Till T Böhlen, Wolfgang Lechner et al.
- [Robot goniophotometry at PTB](#)  
M Lindemann, R Maass and G Sauter



**ECS** The Electrochemical Society  
Advancing solid state & electrochemical science & technology

### 242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Early hotel & registration pricing ends September 12

Presenting more than 2,400 technical abstracts in 50 symposia

The meeting for industry & researchers in

**BATTERIES**  
**ENERGY TECHNOLOGY**  
**SENSORS AND MORE!**

 Register now!

  **ECS Plenary Lecture featuring M. Stanley Whittingham,**  
Binghamton University  
Nobel Laureate –  
2019 Nobel Prize in Chemistry



# Selection of rotating entrance window and target parameters for a gas-filled separator operating at high intensive heavy ion beams

D Ibadullayev<sup>1,2,3</sup>

<sup>1</sup> University «Dubna», Dubna, Russia

<sup>2</sup> Joint Institute for Nuclear Research, Dubna, Russia

<sup>3</sup> Eurasian National University, Astana, Kazakhstan

E-mail: dastan\_96.com@mail.ru

**Abstract.** The durability of the targets and entrance window foils of the Dubna gas-filled recoil separator working at high intensive heavy ion beams was considered. The temperature, as a factor determining their durability, was calculated as a function of time in the conditions of their pulsed heating by heavy ion beam, followed by radiative cooling by radiation emitted from their surfaces. The temperatures were calculated for  $^{48}\text{Ca}$  heavy ion beam with intensity expected for the DC-280 accelerator. With the temperature calculated as a function of time, optimal parameters of the entrance window and target operation were chosen.

## 1. Introduction

The detailed study of properties of superheavy nuclei (SHN) in the experiments with the complete fusion reactions induced by the  $^{48}\text{Ca}$  projectile on actinide target nuclei, which lead to  $112 \leq Z \leq 118$  nuclei, implies the use of heavy ion (HI) beams with the intensity significantly higher than the one used earlier in the discovery experiments [1]. Synthesis of SHN with  $Z > 118$  implies the use of the heavier ions than  $^{48}\text{Ca}$  beam particles ( $^{50}\text{Ti}$ ,  $^{54}\text{Cr}$  etc.). High intensities of heavy ion beams should be obtained at the new DC-280 cyclotron, the basic facility of the superheavy element factory. The expected intensity of the heavy ion beams will be  $10 \mu\text{A}$  (see table 1) [2], which is 10 times greater than those obtained at U-400 accelerator presently used for the synthesis of SHN. These beams will be delivered to a new gas-filled recoil separator. The rotating entrance window is the device which separates the internal volume of the separator, filled with hydrogen to a pressure of 1 Torr, from the cyclotron vacuum [3]. At the DC-280 beam intensities and corresponding energies, the specific powers generated inside thin Ti foils used for the window can reach several hundred  $\text{W}/\text{cm}^2$  (see Table).

Obviously, the high specific powers generated by intense heavy ion beams in the entrance window, as well as large doses of the beam, reduce the durability and degrade the performance properties of the titanium foils. It is believed that a degradation of the foils occurs among them due to their exposure at high temperatures [4]. These temperatures are determined by the heating power generated inside them by an intense ion beam. Under the conditions of the gas-filled separator, this heating power can be removed by heat conduction, convection, and radiation processes [5]. One of the ways to significantly reduce the thermal load on the foils is the use of a pulsed mode. In the case of a continuous beam, the pulse mode is realized by rotating of the entrance window.



**Table 1.** Powers (in W/cm<sup>2</sup>) generated inside entrance window  $P_{window}$  at the intensities of heavy ion beams expected at the DC-280 accelerator. The beam energies in the middle of the target layer are also given, as well as the energies absorbed inside the Ti foils of the entrance window  $\Delta E_{window}$  with the thickness 0.71 mg/cm<sup>2</sup> (all in MeV).

Reaction	$E_{lab}$	Intensity	$\Delta E_{window}$	$P_{window}$
$^{48}\text{Ca}+^{238}\text{U}_3\text{O}_8$	234.9	$10^{14}$	13.7	310
$^{48}\text{Ca}+^{238}\text{UO}_2$	234.9	$10^{14}$	13.7	310
$^{50}\text{Ti}+^{238}\text{U}_3\text{O}_8$	259.9	$3 \cdot 10^{13}$	15.6	106.2
$^{54}\text{Cr}+^{238}\text{U}_3\text{O}_8$	285.4	$2 \cdot 10^{13}$	17.6	79.6
$^{58}\text{Fe}+^{238}\text{U}_3\text{O}_8$	311.4	$1 \cdot 10^{13}$	19.7	44.5

The aim of this work is to calculate the temperature of the Ti foils of the rotating entrance window under the intense  $^{48}\text{Ca}$  heavy ion beam with energy 5.3 MeV/nucleon. Based on these calculations, the values of the optimal radius and angular velocity of the entrance window were proposed.

## 2. Temperature of rotating entrance window

The entrance window irradiated by an intensive heavy ion beam is heated as a result of the energy loss of the incident ion in matter. Thus, a  $^{48}\text{Ca}$  beam with the intensity of  $\sim 10^{14} \text{ s}^{-1}$  and the energy of 5.3 MeV/nucleon generates a thermal power of 310 W/cm<sup>2</sup> in the 0.71 mg/cm<sup>2</sup> titanium foil and 115 W/cm<sup>2</sup> in the 0.4 mg/cm<sup>2</sup>  $^{238}\text{UO}_2$  target (see table 1). Such powers, in the absence of an effective heat removal, should lead to an increase in the foil (target) temperature, which should affect their lifetime. The temperature rise can be suppressed by limiting the intensity of the beam, or by providing an effective heat removal from the foil (target).

As was shown in [5] that at relatively low temperatures, all types of heat removal provide cooling of the Ti foil. At such temperatures, the time-dependent differential equation, which takes into account the heat sink caused by heat conduction, convection, and radiation, seems to be exhaustive for solving the heat conduction problem [6]. At the same time, at high intensities of heavy ion beams, the thermal powers generated in the foil, according to the estimates, lead to temperatures exceeding 700K. At such temperatures, the main way of cooling is the heat removal due to the radiation emitted from the surfaces of the foil. This circumstance makes it possible to write a time-dependent equation corresponding to heat exchange process for rotating window foils bombarded by an ion beam. In calculations for thin Ti foil, thermal conductivity can be neglected [4], and the temperature corresponds to the Stefan-Boltzmann law. The application of this simplification is determined by the ratio of the Ti foil thickness  $d$  to the surface area of the foil  $F$ :

$$\frac{d}{F} \ll \frac{\varepsilon \sigma_{SB}}{6\lambda} T^3, \quad (1)$$

where  $\lambda$  is thermal conductivity,  $\varepsilon$  is full hemispherical emissivity  $\sigma_{SB} = 35.365 \text{ MeV (s cm}^2 \text{ K}^4)^{-1}$  is the Stefan-Boltzmann constant. The fulfillment of this inequality allows for the calculation of the temperature Ti foil.

In the case of a rotating window, we deal with heat exchange processes that depend essentially on time. There are a heating and cooling of the window during a full revolution. Heating and cooling correspond to the times during which the window element is under the beam  $t_{on}$  and out of the beam  $t_{off}$ . These values are determined by the angular velocity of the window  $\omega$ , its central radius  $R$  (distance from the axis of rotation to the center of the beam spot), and radius of the beam spot  $r$ . Taking into account that  $R \gg r$ , we have:

$$t_{on} = r/(\pi\omega R) \quad t_{rev} = 1/\omega \quad t_{off} = t_{rev} - t_{on}, \quad (2)$$

where  $t_{rev}$  - the time of a complete wheel revolution. If inequality (1) is satisfied, we can write a differential equation based on the energy conservation law in relation to the temperature of the foil  $T(t)$  for any point of the foil [4]:

$$\frac{I_b(t)}{F} \Delta E + 2\varepsilon\sigma_{SB}T_0^4 = 2\varepsilon\sigma_{SB}T^4(t) + c\rho d \dot{T}(t), \quad (3)$$

where  $\frac{I_b(t)}{F}$  is the intensity of a beam per unit area,  $\Delta E$  is the energy of the beam absorbed by the foil. Thus,  $\frac{I_b(t)}{F} \Delta E$  is the beam power released per unit area of the foil (see table 1),  $c$  and  $\rho$  are the specific heat capacity and density of the foil, respectively, and  $T_0$  is the temperature of the environment.

Differential equation (3) can be integrated step by step depending on the presence (absence) of the beam. As a result, the temperature of the foil, depending on time, is determined by the following expression [7]:

$$t = t_f + \frac{T_\infty}{2A} \cdot \left\{ \operatorname{arctanh} \left[ \frac{T_\infty(T - T_f)}{T_\infty^2 - TT_f} \right] + \operatorname{arctan} \left[ \frac{T_\infty(T - T_f)}{T_\infty^2 + TT_f} \right] \right\}, \quad (4)$$

where

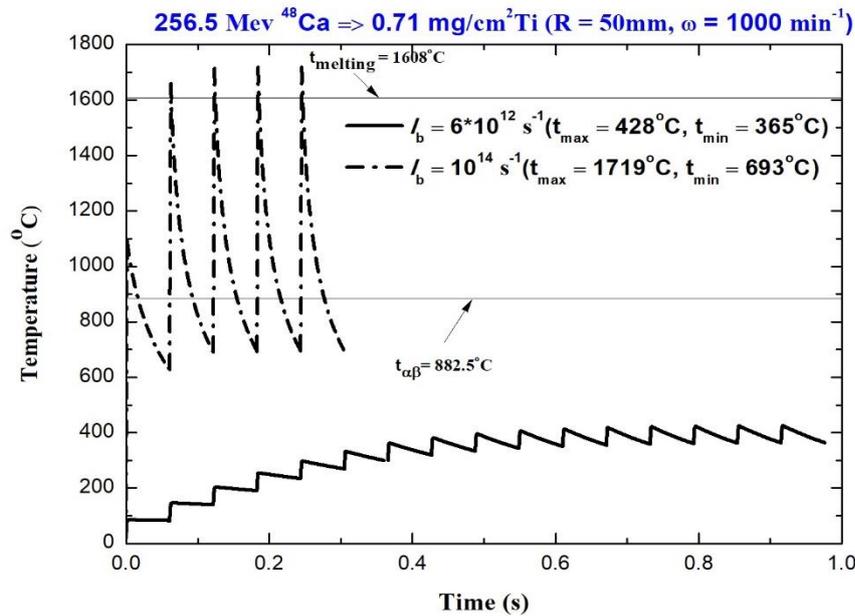
$$A = \frac{(2\varepsilon\sigma_{SB}T_\infty^4)}{c\rho d}, \quad T_\infty = T_0(1+B)^{1/4} \quad \text{and} \quad B = \frac{\left[ \frac{I_b(t)}{F} \Delta E \right]}{2\varepsilon\sigma_{SB}T_0^4} \quad (5)$$

and  $t_f$  is the time of the beginning or of the end of the heating (cooling) pulse,  $T_f$  is the temperature corresponding to this time. The coefficient  $B$  corresponds to the ratio of the power absorbed by the foil, from the beam and from the environment. The expression  $t(T)$  (4) corresponds to the time intervals of the beam  $t_{on}$  and  $t_{off}$  (2). Thus, we obtain the temperature dependence on time for any point of the circle corresponding to the radius  $R$  and angular velocity  $\omega$  of the rotating entrance window. With such a consideration, the distribution of the beam intensity along the radius  $r$  is not taken into account.

### 3. The application of calculations for the choice of the DGFRS entrance window design, which operates at high intensive heavy ion beams

The U-400 isochronous cyclotron is designed to accelerate heavy ion beams with  $A/Z = 8-10$  and energies of 4.5–9 MeV/nucleon. This accelerator produces  $^{48}\text{Ca}$  beams with the intensity of  $6 \cdot 10^{12} \text{ s}^{-1}$  for experiments on the synthesis of SHN with DGFRS. As mentioned above, one of the main elements of the separator is the rotating entrance window. The radius and angular velocity of the entrance window correspond to 50 mm and 16.4 rps, respectively. These parameters of the entrance window ensured stable operation of DGFRS for a sufficiently long beam time.

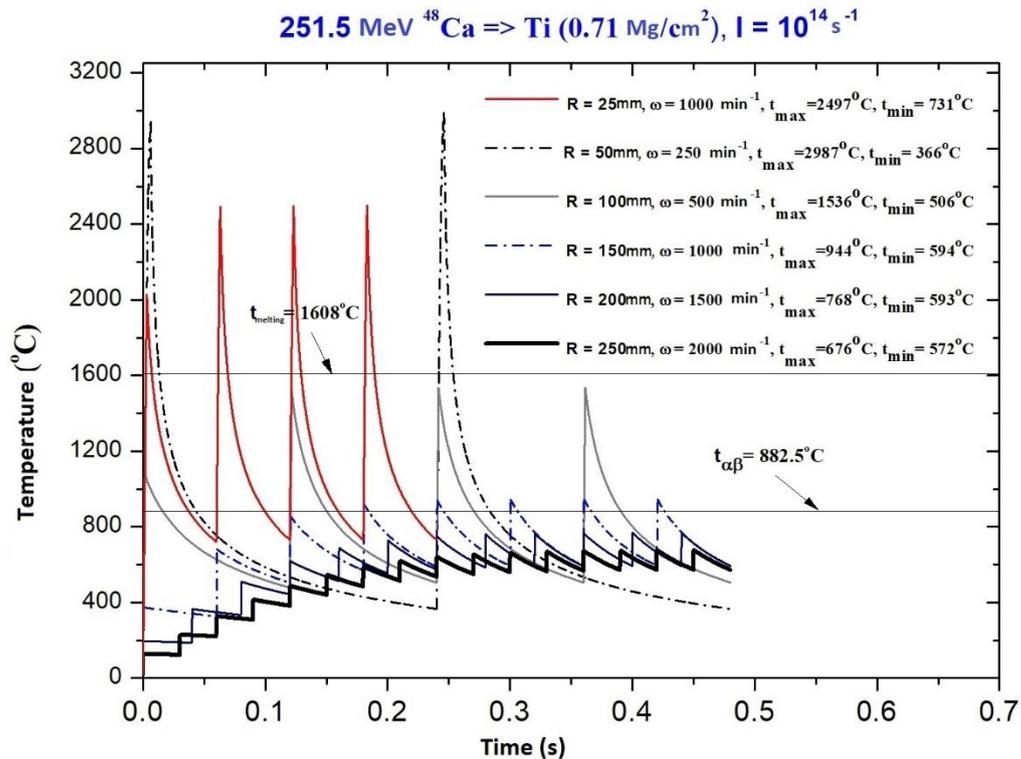
Figure 1 shows the dependence of temperature as a function time for the rotating entrance window [4] calculated with the expression (4). The calculations were performed for the  $^{48}\text{Ca}$  beam intensity of  $I = 10^{14} \text{ s}^{-1}$ , beam radius  $r = 0.4 \text{ cm}$  and an entrance energy  $E = 256.5 \text{ MeV}$ . The calculation was carried out using the angular velocity and the central radius of the entrance window, the same as was used in the DGFRS experiments [1, 8, 9]. The results of this calculation are compared with those obtained at intensity  $I = 6 \cdot 10^{12} \text{ s}^{-1}$ , typical for the experiments conducted at U-400 [1, 8, 9].



**Figure 1.** Temperature dependence of Ti foil with a central radius  $R$  and angular velocity  $\omega$ , irradiated by a  $^{48}\text{Ca}$  ion beam with intensities  $I$ , calculated using the expression (4)

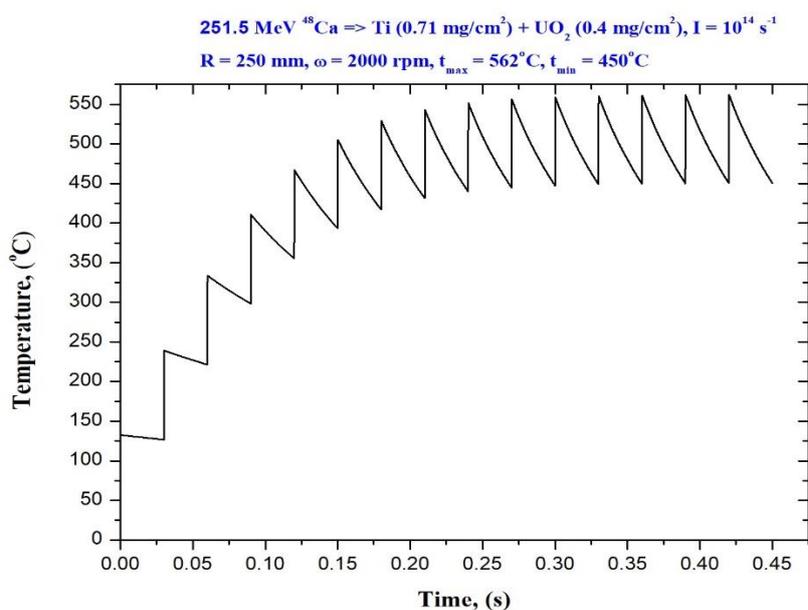
As one can see in figure 1, the maximum temperature of the foil under the beam intensity of  $6 \cdot 10^{12} \text{ s}^{-1}$  slightly exceeds  $400^\circ\text{C}$ . It is much lower than the phase transition temperature  $t_{\alpha\beta}$  in the titanium crystal lattice noted in the figure. Currently, the operation of the existing entrance window of the separator corresponds to this temperature mode. The temperature of the entrance window under the beam intensity of  $10^{14} \text{ s}^{-1}$  strongly differs from the one at  $6 \cdot 10^{12} \text{ s}^{-1}$ . The maximum temperature of the foil exceeds its melting point and far exceeds the phase transition temperature. Thus, at these parameters of the entrance window and the beam intensity expected from the DC-280 cyclotron, the titanium foil can melt at the very beginning of work. A large difference between the maximum and minimum temperatures should create an additional pulsed mechanical load on the foil due to thermal stresses. This, in turn, can reduce the durability of the entrance window.

In search of entrance window parameters, such as the  $\omega$  and  $R$ , additional temperature calculations were performed for heavy ion beams expected from the DC-280 cyclotron. Figure 2 shows such calculations for titanium foil irradiated by the  $^{48}\text{Ca}$  ion beam. As might be expected, the results of these calculations for a lower angular velocity and smaller radius, corresponding to a long-term  $t_{on}$  and  $t_{off}$ , as compared with these parameters used in the performed experiments [1] (see figure 1) show higher maximums for the foil temperatures. The differences between the maximal and minimal temperatures also increase. Thus, the durability of the foil with parameters corresponding to the three top lines shown in figure 2, becomes even more doubtful than in the cases shown figure 1. At the same time, higher angular velocity and larger radius, corresponding to shorter times of  $t_{on}$  and  $t_{off}$ , as compared with those used in the experiments (see figure 1), lead to lower maximums of the foil temperatures. The differences between the maximal and minimal temperatures are reduced. So, in the cases of the parameters corresponding to the bold line shown in figure 2, one can expect a maximal foil temperature not exceeding  $800^\circ\text{C}$  and the difference between maximal and minimal temperatures below  $150^\circ\text{C}$ .



**Fig. 2.** Temperature dependence of Ti foil for different radii  $R$  and angular velocities  $\omega$  (indicated in the figure), located under a  $^{48}\text{Ca}$  beam with an intensity of  $10^{14}$  and energy of 251.5 MeV.

Taking into account the additional cooling induced by the convection process, it can be stated that such parameters of the entrance window as angular velocity  $\omega = 2000 \text{ min}^{-1}$  and wheel radius  $R = 250 \text{ mm}$  allow  $0.71 \text{ mg/cm}^2$  titanium foils to withstand thermal loads generated by  $^{48}\text{Ca}$  beams with energies of  $\sim 5.3 \text{ MeV/nucleon}$  at the intensities expected on the DC-280 cyclotron (see table 1).



**Figure 3.** Temperature versus time for a  $^{238}\text{UO}_2$  target.

Similar calculations were performed for a rotating target with parameters that seem to be optimal as in the case of the entrance window (see figure 2). Figure 3 shows the temperature dependence for a  $\text{UO}_2$  target deposited on the  $0.71 \text{ mg/cm}^2$  titanium backing for the  $^{48}\text{Ca}$  ion beam intensity of  $10^{14} \text{ s}^{-1}$ . As in the case of a rotating entrance window, bearing in mind some additional cooling on the both sides of the target provided by the convection process, one can expect that the selected parameters (angular velocity and radius) for the target will allow withstanding the thermal load created by the heavy ion beams expected from the DC-280 cyclotron.

#### 4. Conclusion

The high intensities of heavy ion beams used in the experiments on the synthesis of SHN affect the materials of targets and foils used in these experiments with the use of DGFRS. The specific heating power realized into these elements corresponds to several hundred  $\text{W/cm}^2$ . It makes these elements critical in future experiments on the synthesis of SHN at the DC-280 cyclotron, which will be commissioned in the nearest future. The temperatures of titanium foils as a function of time, were calculated under the conditions of their pulsed heating by a HI beam and radiative cooling by radiation emitted from their surfaces. Such a pulsed mode is inherent in the operation of DGFRS during experiments conducted with the rotating target and entrance window, irradiated by a continuous HI beam. The temperatures of titanium foils of the entrance window under the  $5.3 \text{ MeV/nucleon } ^{48}\text{Ca}$  heavy ion beam with the intensity expected from the DC-280 cyclotron were calculated. Based on these calculations, the optimal radius and rotational speed of the entrance window were proposed for DGFRS operating at high intensive heavy ion beams.

#### References

- [1] Oganessian Yu Ts and Utyonkov V K 2015 *Nucl. Phys. A* 944 62-98
- [2] Gulbekian G G, Dmitriev S N, Oganessian Yu Ts, Gikal B N, Kalagin I V, Bogomolov S L, Ivanenko I A, Kazarinov N Yu, Ivanov G N and Osipov N F 2016 *21st International Conference on Cyclotrons and their Applications (Zurich)* pp 278-80
- [3] Ivanov G N 1991 *Heavy Ion Physics Scientific Report* 32 162-63
- [4] Yntema J and Nickel F 1978 *Experimental Methods in Heavy Ion Physics Lecture Notes in Physics* 83 206-235
- [5] Sagaidak R N 2017 *PEPAN Letters* 14 4
- [6] Wong H Y 1977 *Handbook of Essential Formulae and Data on Heat Transfer for Engineers* ed. Longman (London)
- [7] Marx D, Nickel F, Munzenberg G, Guttner K, Ewald H, Faust W, Hofmann S, Schott H J and Thalheimer W 1979 *Nucl. Instrum. Methods Phys. Res.* 163 15-20
- [8] Oganessian Yu Ts *et al.* 2011 *Phys. Rev. C* 83 054315
- [9] Utyonkov V K *et al.* 2015 *Phys. Rev. C* 92 034609