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Target cooling for high-current experiments at SHIP

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Abstract

In order to further increase the intensity of ion beams used in high-current experiments, e.g. the synthesis of heavy and superheavy elements, it is necessary to develop methods for cooling the targets sufficiently below the melting point which is particularly low in the case of metallic lead and bismuth targets. In this paper we describe measurements for various fixed targets and rotating target wheels in vacuum as well as in a stationary He-gas and a He-gas flow as cooling medium. As a result improvements of the target system are suggested, which will allow for a considerable increase of the beam intensity.

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Keywords: Gas cooling; Target wheel; Target durability; Heavy elements

1. Introduction

The study of superheavy nuclei demand the application of experimental methods which are at the limits of technical possibilities. During the last 20 years at GSI in Darmstadt isotopes of new elements with $Z = 107$–112 were produced and identified using the velocity separator SHIP [1]. In these experiments superheavy nuclei were produced by complete fusion reactions based on lead and bismuth targets and most neutron-rich stable projectiles like ^{54}Cr, ^{58}Fe, ^{62,64}Ni, and ^{70}Zn. The cross-sections decrease exponentially with increasing proton number. For element 112 the cross-section reaches a value of 0.5 pb [2] and the detection rate is about one nucleus per 14 days at an average beam intensity of 0.25 pμA (1 pμA $= 6.25 \times 10^{12}$ particles/s). In order to synthesize high Z elements in reasonable irradiation times, it is necessary to increase the beam intensity. Higher production rates will also enable more detailed investigation of nuclear properties of known lighter elements.

Lead and bismuth have low melting points of 600 and 544 K, respectively. Mounting the targets on a rotating wheel allowed to increase the beam

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intensity about 15 times compared to the use of fixed targets [3]. In current SHIP experiments 450 μg/cm^2 thick lead or bismuth targets are used. The targets are evaporated on a carbon backing foil of 40 μg/cm^2 and covered with a 10 μg/cm^2 carbon layer to increase the emissivity and to reduce sputtering of target material [4,5]. Assuming an ^{40}Ar beam intensity of 1 pμA and 5 MeV/u energy the deposited power in the target will be 3.14 W and the power density for a SHIP condition will be 4 Wcm^{-2} [6]. This power must be continuously removed from the target by radiation and by heat conduction through the target towards its frame. In order to increase the beam intensity and to avoid target melting, the heat removal from the target has to be enhanced. This could be accomplished by improving the two mentioned cooling processes, radiation and conduction, or/and by applying of a third possible cooling mode, cooling via conduction and convection in a gas. As known from experiments at gas-filled recoil separators, targets used there withstand higher beam intensities than those operated in vacuum.

Our aim was to test the cooling efficiency of a stationary gaseous medium and a directed gas flow and to determine the optimum gas pressure. The resulting observations serve as a base for the design and construction of a new target chamber at SHIP. A previous similar study was performed by Nitschke [7], who also investigated the influence of different cooling gases, gas temperatures and gas flows on the target temperature. However, the conditions in [7], namely the higher target temperature and a high gas pressure of 1 atm differ considerably from ours. Low melting points of Pb and Bi limit our maximum temperature and the impossibility of using thick vacuum windows does not allow for using high gas pressures.

2. Experimental setup

The schematic view of the test setup is shown in Fig. 1. It consists of three aligned vacuum chambers, each one evacuated by a turbomolecular pump. The target and the gas inlet were mounted into the first chamber. The heavy-ion beam was simulated by a 14 keV electron beam produced by an electron gun placed in the third chamber. The second chamber served as a second stage in the differential pumping system. The first and second chamber were equipped with turbomolecular pumps with a volume flow rate of 1450 l/s for helium and the third chamber by a smaller one with volume flow rate of 350 l/s for helium.

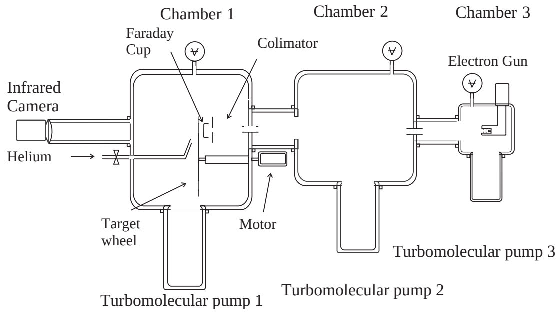


Fig. 1. Schematic view of the test bench.

We chose helium as cooling gas because of its small atomic size resulting in a weak influence on the electron (and later also heavy ion) beam. The maximum gas pressure in the first chamber is determined by the conditions required at SHIP, where the distance from the target to the first quadrupole magnet is only about 60 cm. Over this distance the pressure must drop down to a value of at least 10^{-5} mbar because of the high-voltage electrostatic dipole in SHIP. The diameter of the tube between the last pumping stage in front of SHIP and the target must be at least 4 cm.

Two modes of gas cooling were tested:

(a) In the first mode the target was cooled in a gas atmosphere at a chosen pressure flowing slowly through the chamber.
(b) In the second mode a helium jet created with a Laval-like nozzle was directed to the interaction spot of the target and beam. Thereby the gas density in the interaction area was significantly higher than in the rest of the chamber. The nozzle had a minimum diameter 0.2 mm in the middle and a maximum diameter of 1 mm at the end (see Fig. 2).

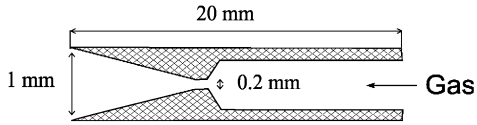


Fig. 2. Schematic view of the applied Laval-like nozzle.

The pressure in different chambers was measured near the walls of the chambers and in the first chamber at a long distance from the nozzle. The accuracy of the pressure measurement was better than 30%.

In front of the target we mounted a collimator and a movable Faraday cup. The collimator assured a well defined beam spot on the target and with the Faraday cup the electron current incident on the target was measured. During all measurements a homogenous beam intensity across the beam spot was provided.

For SHIP experiments two types of targets, fixed and rotating, are employed. Fixed targets usually have a diameter of 15 or 20 mm and are mounted on a target ladder that can be moved in and out of the beam. For the rotating mode eight circular ring sector targets ($110 \times 23\ \mathrm{mm}^2$) are mounted on a wheel of 310 mm diameter that rotates synchronously to the beam pulsing.

The temperature of the target was monitored using a fast infrared camera which was mounted directly to the vacuum chamber. The germanium front lens of the camera served as a window to separate the high vacuum in the chamber from the outer atmosphere. The distance between the lens and the target was 150 cm. The position resolution at that distance was 1 mm and the time resolution of the camera was 20 ms. For the temperature measurement the camera uses the part of the infrared spectrum from 7.5 to 14 μm.

The accuracy of the whole measurement depends on the temperature measurements as well as on the accuracy of the beam current measurement. During the experiments the uncertainties of both contributions were of the order of 5–15% and the estimated total error was less than 25%. Relative measurements are correct within an error bar of 10%.

3. Temperature measurement

The infrared camera calculates the temperature of an object making use of three laws used in infrared thermography: Planck law, Wien's displacement law and Stefan–Boltzmann law. The crucial parameter is the emissivity of the object, which strongly depends on material properties like color, roughness, etc. [8]. Therefore, we decided to measure the emissivity of each of the targets and not to use tabulated values.

We found that the emissivity of the lead targets with carbon backings changes with time. New targets had a lower emissivity (0.11–0.17 from the 10 $\mu\mathrm{g/cm}^2$ side, 0.2–0.25 from the 40 $\mu\mathrm{g/cm}^2$ side) compared to that of 'older' not irradiated targets and also of irradiated targets (emissivity 0.49–0.75 from both sides). This change is explained by oxidation of the lead layer in air and a modification of the carbon layer during irradiation, respectively.

The emissivity was measured in the following way. We heated a copper block with the target fixed onto it in good thermal contact to a reference temperature which was determined by a thermocouple inside the block. Then we varied the adjustment of the emissivity of the IR-camera until the camera reading showed the same reference temperature. The accuracy of this procedure was better than 10%.

Four different processes determine the temperature of a target irradiated by a heavy-ion beam in vacuum or a gaseous medium:

(a) Heat production in the target by energy loss of the beam.
(b) Radiation cooling.
(c) Thermal conduction through the target towards its frame.
(d) Conduction and convection through the gas surrounding the target.

On the basis of theoretical consideration a computer program was developed, which numerically calculates the time dependence of the target temperature for various conditions [9]. In Section 4 experimental data will be compared to these calculations.

4. Results and discussion

4.1. Radiation and conductive cooling

In vacuum radiation is the main cooling process, at least for thin layers with a relative low conductivity like Pb. Because of the lack of appropriate targets, the influence of conductive cooling could not be measured but it was estimated using the theoretical model. The thickness of the conductive layer together with the coefficient of thermal conductivity are the most important parameters. Amorphous carbon which is the state of the carbon backing has a low thermal conductivity of 5 $Wm^{-1} K^{-1}$ [10]. Therefore the lead layer with a tabulated value of thermal conductivity of 35 $Wm^{-1} K^{-1}$ [10] is the only layer to be considered in the conduction process.

We tried to reproduce the large number of measured temperature values by calculations. In vacuum without gas cooling the agreement was fairly good. If the conductivity was not considered, the calculations gave (25–35)% higher values than the measured ones. This difference is ascribed to conductive cooling in the lead target. For the rotating targets, where conduction only in radial direction contributes, the influence of conduction is even less.

By using a pulsed beam with the same mean intensity as a continuous beam, the heat production will be concentrated in the short time during the beam pulse. In our measurements it was not possible to experimentally simulate the pulsed beam, at least not for a static target. Therefore calculations for both the continuous and the pulsed beam were compared. In Fig. 3 the calculated temperature evolution for two lead targets with different emissivity ($\varepsilon_{tot} = 0.31$ and 1.05, respectively) is shown. A pulse structure typical of the conditions at SHIP with 5.5 ms pulse and 14.5 ms pause width was used in the calculation. The power necessary to reach 150°C with a continuous beam was calculated for both targets. Then the temperature dependence for a pulsed beam of the same mean power was calculated. In both cases, in equilibrium, the mean value of temperature of the pulsed beam was equal to the temperature using the continuous beam, because the average deposited heat is the same. However, the differences between the maximum and minimum temperature reached in the target are increasing with increasing emissivity, which is a result of the higher beam power in the latter case.

4.2. Fixed target

The influence and efficiency of the gas cooling can be expressed in various approaches. Here it will be presented as the increase of the beam intensity necessary to heat the target to a given reference temperature for different helium pressures.

The two different gas-cooling modes are compared in Fig. 4. We heated a lead target with an emissivity of $\varepsilon = 0.31$ to a temperature 150°C. In one case it was cooled by a slowly flowing He atmosphere and in the second case the target was

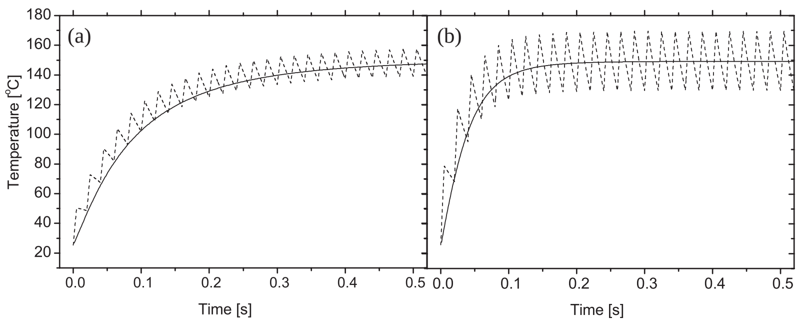


Fig. 3. Calculated target temperature time dependence using a continuous (full line) and pulsed beam (dashed line) in vacuum for reaching a final average temperature of 150°C. Two static targets with different emissivity are compared: (a) $\varepsilon_{tot} = 0.31$ and $P_0 = 0.079$ Wcm^{-2}; (b) $\varepsilon_{tot} = 1.05$ and $P_0 = 0.172$ Wcm^{-2}.

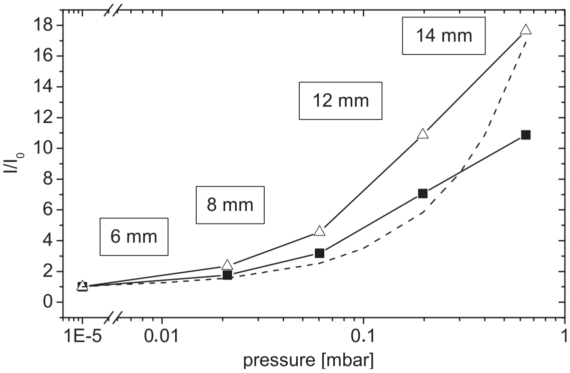


Fig. 4. Gas cooling of a fixed lead target ($\varepsilon_{tot} = 0.31$). I_0 is the current needed to heat the target to 150°C in vacuum ($P_0 = 0.071$ Wcm^{-2}, I is the current needed at the applied pressure. Cooling in He atmosphere (full squares), using a nozzle (open triangles) and calculations for He atmosphere (dashed line) are shown. The distances of the nozzle from the beam spot at the various measuring points are given.

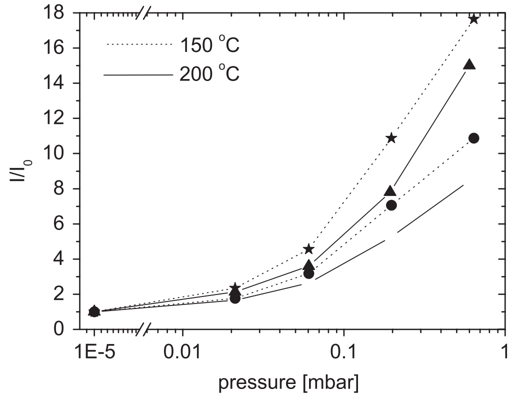


Fig. 5. Influence of different working temperatures. Measurements with the same target ($\varepsilon_{tot} = 0.31$) at temperature 150°C (circles—without nozzle; stars—with nozzle) and 200°C (squares—without nozzle; triangles—with nozzle).

cooled with a directed stream of helium from the Laval nozzle. In vacuum a power $P_0 = 0.071$ Wcm^{-2} was needed to heat the target to the reference temperature. To keep the same temperature in a helium atmosphere of 0.64 mbar, the power could be increased to 0.777 Wcm^{-2}, which is 11-times more than that in vacuum. Using a directed stream of helium from a nozzle an almost 18-times larger value compared to that in vacuum was obtained. The distance between nozzle and target, which was most effective for cooling, increased with increasing gas pressure and flow (see Fig. 4). This is probably connected with the processes of forming a gas jet by the Laval nozzle. The nozzle was positioned at a distance of 6 mm to the target at low pressure. The distance was increased up to 14 mm at 0.64 mbar. The flow was directed to the target under an angle of 40°.

Using two nozzles instead of one directed to same position of the target from opposite sides did not improve the cooling efficiency. For the same pressure in the chamber the flow of helium is shared between the two nozzles and as a result the same number of gas molecules hit the beam spot and carry away the same amount of heat as in the case of only one nozzle.

In Fig. 4 also the calculated beam power for the stationary He atmosphere is shown. Below a pressure of 0.3 mbar the calculations underestimate the experimental values, but for higher pressures the calculated values start to increase steeply. This turning point refers to the pressure at which the distance between two subsequent molecule interactions is so short that the condition of large mean free path assumed in calculations is not fulfilled. To fit the experimental value of $I/I_0 = 10.9$ at 0.64 mbar, the accommodation coefficient α must be set to 0.58. This coefficient is proportional to the energy carried away by one molecule of gas and is usually determined experimentally [11].

We also measured the influence of the working temperature. The power P_0 necessary to reach 150°C was 0.071 Wcm^{-2}. For the same target, but a reference temperature of 200°C, a power of $P_0 = 0.122$ Wcm^{-2} was measured. The effects of the working temperature on the deposited power are shown in Fig. 5 and summarized in Table 1.

Using a target with a higher total emissivity allowed to increase in vacuum the intensity. The heat removed by the helium, what is the main cooling process in He atmosphere, does not depend on the emissivity. As a consequence the accepted intensity I by the target is increased only slightly in comparison with the respective low

Table 1
Power in Wcm^{-2}, which can be deposited in a fixed target ($\varepsilon_{tot} = 0.31$) in order to reach the reference temperature $T_{ref} = 150°C$ and $T_{ref} = 200°C$ for various conditions

$\varepsilon = 0.31$	150°C		200°C	
	P (Wcm^{-2})	I/I_0	P (Wcm^{-2})	I/I_0
Vacuum	0.071	1.0	0.122	1
Without nozzle at 0.064 mbar	0.226	3.2	0.321	2.6
Without nozzle at 0.64 mbar	0.777	10.9	1.029	8.4
With nozzle at 0.064 mbar	0.325	4.6	0.437	3.6
With nozzle at 0.64 mbar	1.260	17.7	1.827	14.9

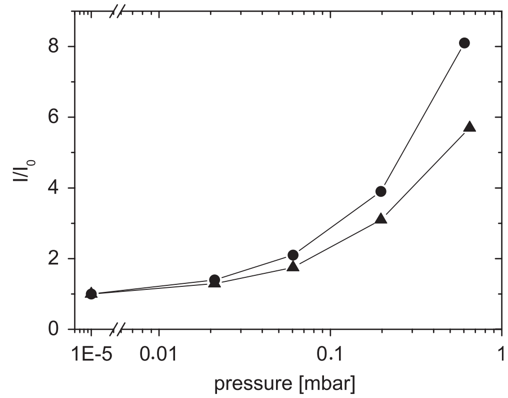


Fig. 6. Influence of different emissivities for a fixed target and stationary He atmosphere. Measurement at temperature 170°C and targets with the same thickness with total emissivity $\varepsilon_{tot} = 1.05$ (triangles) and $\varepsilon_{tot} = 0.4$ (circles). Note that the reference current I_0 is higher in the case of $\varepsilon_{tot} = 1.05$ ($P_0 = 0.126\ Wcm^{-2}$) compared to the case of $\varepsilon_{tot} = 0.4$ ($P_0 = 0.108\ Wcm^{-2}$).

emissivity target measurement (see Fig. 6 and Table 2).

As in the previous section, calculations were performed also for a pulsed beam (see Fig. 7). A pulsed beam and gas cooling ($p = 0.64$ mbar, using nozzle) gives rise to more pronounced extremal values. Maximum values of 245°C and minimum values of 76°C are reached. In order to keep the maximum temperature at 150°C the beam power has to be decreased to $0.43\ Wcm^{-2}$ compared to $0.78\ Wcm^{-2}$ with a continuous beam.

4.3. Rotating target

The main effort of our work was dealing with the rotating target wheel, since this is exclusively used in heavy-element experiments. In SHIP experiments the target wheel with a diameter of 310 mm rotates with a frequency of 18.75 Hz. The pulse width of the beam is 5.5 ms and the pause

Table 2
Power in Wcm^{-2}, which can be deposited in a fixed target with the emissivity $\varepsilon_{tot} = 0.4$ and $\varepsilon_{tot} = 1.05$ in order to reach the reference temperature $T_{ref} = 170°C$ for various conditions

$T_{ref} = 170°C$	$\varepsilon = 0.4$		$\varepsilon = 1.05$	
	P (Wcm^{-2})	I/I_0	P (Wcm^{-2})	I/I_0
Vacuum	0.108	1.0	0.147	1
Without nozzle a 0.064 mbar	0.223	2.1	0.258	1.7
Without nozzle a 0.64 mbar	0.874	8.1	0.845	5.7

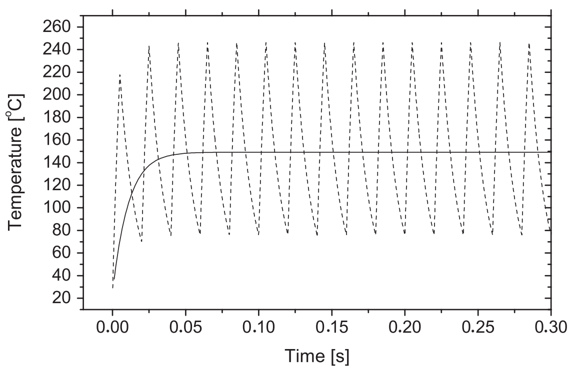


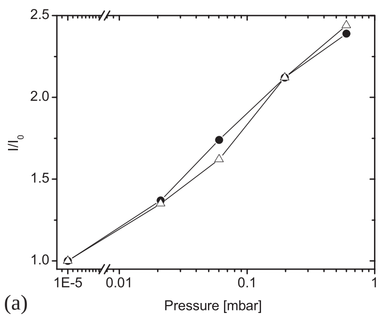
Fig. 7. Calculated temperature curves for a pulsed (dashed line) and continuous beam (full line) in helium atmosphere at a pressure 0.64 mbar. The same target as in Fig. 3a) was used, however with a power $P_0 = 0.78\ Wcm^{-2}$.

width is 14.5 ms. The beam spot is ellipsoidal, typically about 10 mm in radial and 7 mm in azimuthal direction. For these conditions we obtain as irradiation time of a point in the center of the target a value of $t_{in} = 0.38$ ms. For evaluating the out-of-beam period we have to consider that the target wheel is divided into 8 target segments and its rotation is synchronized with the pulsing in such a way that each target is irradiated again after three revolutions (160 ms). Therefore $t_{out} = 160\ \text{ms} - t_{in} = 159.62$ ms.

Because the electron gun was not adapted for delivering a pulsed beam, we approximated the t_{in} and t_{out} values by suitable selection of the rotation speed of the wheel and size of the beam spot. We used a combination of an elliptical spot $6 \times 2.4\ \text{mm}^2$ and a rotation speed of 6.25 Hz which resulted in $t_{in} = 0.39$ ms and $t_{out} = 159.61$ ms. Since a continuous electron beam was used, the measured value of the beam current was multiplied by a factor of $0.275\ (= t_{pulse}/(t_{pulse} + t_{pause}) = 5.5/20\ \text{ms})$ to obtain a mean current comparable with that used at SHIP.

In the measurement with the rotating target we obtained a value of 3.2 Wcm^{-2} to heat the target to 150°C in vacuum which is 45-times more than for the fixed target (0.071 Wcm^{-2}). In Fig. 8 and Table 3 the results of gas cooling in helium atmosphere and using a directed He flow from the Laval nozzle are compared. The targets had an average thickness of 37–460–10 $\mu\text{g/cm}^2$ (C–Pb–C), a total emissivity of $\varepsilon_{tot} = 0.31$ and were heated to a temperature of 150°C. Two conclusions can be drawn. First, the gas cooling is less efficient as in the case of a fixed target, and second, there is no enhancement in cooling observed when the nozzle is used. The power needed to heat the target to the reference temperature at 0.64 mbar was in both cases only 2.4 times higher than in vacuum.

The explanation for both observations have the same origin. As can be seen in Fig. 9 during the short period of irradiation (0.39 ms) the increase



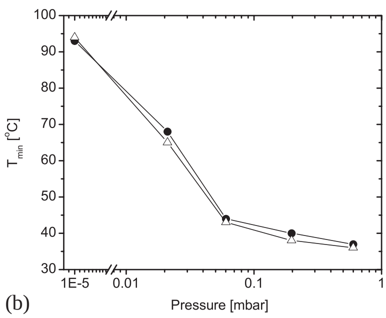


Fig. 8. (a) Relative current (in vacuum $I = I_0$) needed to heat a rotating lead target ($\varepsilon_{tot} = 0.31$) to 150°C in He atmosphere (circles) and using a Laval nozzle (triangles) and (b) minimal temperature of the target spot, just before it enters the beam spot again.

Table 3
Power in Wcm^{-2}, which can be deposited in the target to reach a reference temperature $T_{ref} = 150$°C for various beam structures, pressures, cooling modes and target emissivities using a rotating target wheel.

$T_{ref} = 150$	Standard pulsed beam[A]				Double speed[B]	Continuous beam[C]
	With nozzle	Without nozzle				
	$\varepsilon = 0.31$	$\varepsilon = 0.31$	$\varepsilon = 1.48$	$\varepsilon = 0.31$	$\varepsilon = 0.31$	$\varepsilon = 0.31$
Vacuum	2.9	3.2	5.8	3.1	3.6	8.4
0.064 mbar	4.8	5.7	8.8	5.1	6.8	20.1
0.64 mbar	7.2	7.8	13.2	6.5	9.4	35.3

[A] $t_{in} = 0.39$ ms $t_{out} = 159.6$ ms, [B] $t_{in} = 0.2$ ms $t_{out} = 79.8$ ms, [C] $t_{in} = 0.24$ ms $t_{out} = 49.8$ ms

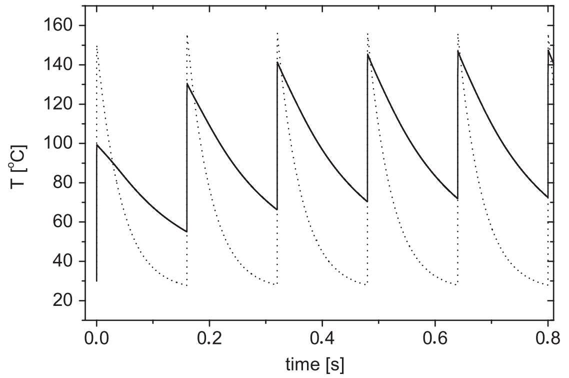


Fig. 9. Calculated temperature curves for rotating lead target in vacuum at $P_0 = 3.3\ \mathrm{Wcm^{-2}}$ (full line) and at 0.064 mbar He at $P_0 = 7.9\ \mathrm{Wcm^{-2}}$ (dashed line). Irradiation time $t_{in} = 0.39$ ms, beam-off time $t_{out} = 159.6$ ms.

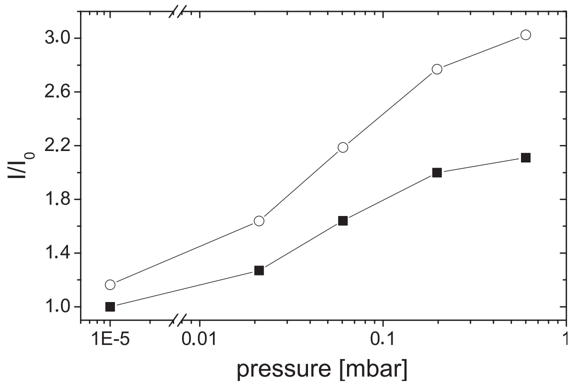


Fig. 10. Relative beam current needed to heat the rotating lead target ($\varepsilon_{tot} = 0.42$) to a temperature of 150°C at different pressures for standard pulsed beam $t_{in} = 0.39$ ms, $t_{out} =$ 159.6 ms and (squares) and double speed $t_{in} = 0.2$ ms, $t_{out} =$ 79.8 ms (circles). I_0 is the current in the case of standard beam in the vacuum. See text for further explanation.

of the temperature is very fast. Then, during the relatively long beam-out time (159.6 ms) the target cools down until the next irradiation starts. The maximum temperature is reached after five cycles in vacuum and after two cycles at a pressure of 0.064 mbar. The process of heat generation in the target is much faster than any form of cooling. We can estimate the rates for all processes. In vacuum a power of 1.34 W (average power divided by a duty factor of 0.275) is released in the target by the beam particles (spot size $6 \times 2.4\ \mathrm{mm^2}$). Radiation heat rate from the hot spot is 5 mW and conduction heat removal is 3 mW maximum. At a pressure of 0.64 mbar not more than 134 mW of the heat will be removed by convection (gas cooling).

Accordingly, the time in which the increased pressure using a Laval nozzle affects the target is too short (<2 ms) for cooling because before the nozzle can remove substantial heat the hot spot has disappeared from the jet. Due to the long beam-off period a higher emissivity and/or conductivity of the target will improve the target performance in vacuum. The heat from the target is removed faster and in the subsequent irradiation the temperature reaches lower values than in the case of a target with low emissivity or conductivity. All results are summarized in Table 3.

Working at a higher reference temperature has similar effect as in the case of a fixed target. The accepted power is higher and the obtained increase in beam intensity using helium cooling is relatively small.

One possibility to improve the target's heat acceptance is to increase the rotation speed of the target wheel. On the one side the irradiation time becomes shorter and the energy is distributed over a larger target area, but on the other side also the beam-out period is shorter so the target has less time to cool down. To see the effect, the speed of rotation was doubled ($t_{in} = 0.2$ ms, $t_{out} = 79.8$ ms). Lead targets with a total emissivity of $\varepsilon_{tot} = 0.42$ were used in this measurement. Results compared to the standard rotation speed are shown in Fig. 10 and Table 3. In vacuum only an enhancement of 20% was observed at higher speed. At increasing pressure the cooling efficiency for a faster rotating wheel was larger by a factor of three at 0.64 mbar.

It was discussed in Sections 4.1 and 4.2 that using a pulsed beam instead of a continuous beam results in higher maximal temperature. Hence a logical step is to use a continuous beam. Using a current SHIP target set-up this will result in a beam-out period three times shorter ($t_{out} = 53.3$ ms) while the beam-on time will remain unchanged ($t_{in} = 0.38$ ms). In Fig. 11 an experimental comparison of these two modes is shown. A circular beam spot of 4.7 mm in diameter and a wheel rotation frequency of

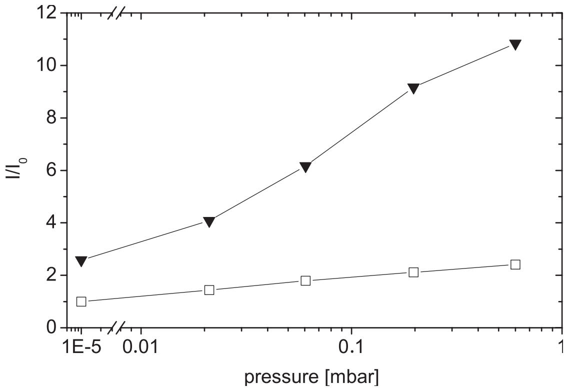


Fig. 11. Relative beam current needed to heat a rotating lead target ($\varepsilon_{tot} = 0.31$) to a temperature of 150°C at different pressures. Squares and triangles mark pulsed and continuous beam, respectively.

20 Hz were used to simulate the conditions of a continuous beam. The values for $t_{in} = 0.24$ ms and $t_{out} = 49.8$ ms are close to the calculated ones. Already in vacuum an enhancement of a factor of 2.6 was measured. Cooling with helium at a pressure of 0.64 mbar results in a power increase by a factor of almost 11 (35 Wcm^{-2}) compared to the presently used pulsed beam and rotating wheel technique in vacuum.

5. Summary and outlook

For a fixed target in vacuum an increased emissivity or/and conductivity of the target allows to enhance the intensity of the beam up to a factor of two. Adding helium cooling with a directed stream from a Laval nozzle results in another factor of 10–20 (see Table 1).

The results for cooling a rotating target wheel are more complex (see Table 3). At the presently used duty factor of the beam and rotation frequency of the target wheel, only a 2.4 times higher intensity was measured at a He pressure of 0.64 mbar. Using a target with higher emissivity an increase of the beam intensity by 81% can be achieved. Here the limiting factor is the fast process of heat production in the spot of irradiation, which cannot be significantly reduced by any cooling process.

Increasing the speed of rotation by a factor of two did result only in an increase of beam intensity by 20% in vacuum. However, together with the gas cooling an almost three times higher value was achieved. A more effective change would be to increase simultaneously the radius of the wheel.

Most promising seems to be the application of a continuous beam. Measurements showed that already in vacuum this would lead to an increase of the beam current of at least a factor of two. With gas cooling even a total gain factor of 11 was achieved.

A further improvement of the gas cooling efficiency could be achieved by cooling the gas itself. The amount of heat carried away by the gas depends linearly on the temperature difference between the gas and the target. By cooling the gas for example to the temperature of liquid nitrogen a significant cooling effect is expected.

One should keep in mind that all results presented here are performed in the low temperature range between 100°C and 200°C. At higher temperatures the principles of heat production and removal are the same, however, the different processes will contribute differently to the total cooling. Higher temperatures could be achieved with chemical compounds as target material. Presently under investigation at SHIP are layers of PbS and Bi_2O_3.

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