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Joachim M. Nitschke

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A HIGH INTENSITY HEAVY-ION RECOIL-TARGET SYSTEM*

Joachim M. Nitschke

Abstract

The paper describes a target system to be used with heavy-ion beams of high intensities. The principle of gas cooling is explained and the conditions for optimum cooling are evaluated. A theoretical and experimental comparison is made between different cooling gases, window materials, cooling gas temperatures and flows.

*This work supported by the U. S. Energy Research and Development Administration.

A HIGH INTENSITY HEAVY-ION RECOIL-TARGET SYSTEM

Joachim M. Nitschke

A. Introduction

A characteristic of heavy-ion reactions is the large forward momentum imparted to the product nucleus. This has led to the successful development of the recoil-target technique. Most transuranic elements and most isotopes in the trans-lead region were discovered by this technique. The principle is that the target material is made thin enough so that the forward momentum of the product nuclei is sufficient for them to recoil into a gas atmosphere (usually helium at about 1 atm pressure). From there the recoils are swept through a nozzle into a vacuum and impinge on a detection apparatus or are transported through capillaries of various length. The limitations of this technique, however, have become apparent in several experiments. To illustrate this point two cases will be discussed. In the study of the chemical behavior of element 104 (Ref. 1), the yield for the production of isotope $^{261}_{104}$ had to be optimal, the reaction being $^{248}_{\text{Cm}}(^{18}_\text{O}, 5\text{ n})$ $^{261}_{104}$. The target contained 7.66×10^{17} atoms, the reaction cross section was 5 nb, and the maximum beam the $\frac{1}{4}$ inch-diameter target could support without raising its temperature above 500°C was 4.87×10^{12} particles per second. This led to a production rate of 67 atoms of $^{261}_{104}$ per hour. In a similar recent experiment to produce $^{263}_{106}$ (Ref. 2), the cross section was 25 times lower and the production rate reduced to "one or two" atoms per hour. In a future experiment we plan to produce an isotope of element 107, but the predicted cross section

is only 5 to 30 pb (picobarn!) depending on whether ^{19}F or ^{22}Ne is used as a projectile. Given the same conditions as in the 104 experiment, this would result in a production rate of about 2 to 10 atoms per day (!). To build up sufficient statistics several weeks of continuous bombardments would be necessary since it is unlikely that the peak of the excitation function can be calculated with sufficient accuracy. With many other important experiments proposed for the SuperHilac, it would be impossible to obtain such a large amount of beam time and as a consequence the experiment would not be done. There is, however, much interest in studying other reactions with low cross sections besides element 107, in particular in the unknown region of superheavy elements. These considerations led to the development of the high intensity heavy-ion target (HIHIT). This target system also allows an increase in the production rate of already known elements (104, 105, 106) potentially to a level where hitherto impossible experiments with regard to fine structure of α decay, chemical properties, etc., can be carried out.

To become familiar with the present limitations of a typical target, it is useful to refer again to the aforementioned 104 experiment. The target consisted of a 13 μm thick Be backing, 6.35 mm in diameter (2.35 mg/cm^2). The target material itself weighed 1 mg/cm^2 . The ^{18}O beam deposited 9.1 MeV of energy in both the target and the backing. At a beam intensity of 4.87×10^{12} particles per second, the total power dissipated in the target was 7.11 watt, or 22.4 W/cm^2 . In an experiment with Ar ions, the limiting power density was 11 W/cm^2 .

Our experience with other targets shows that 22 W/cm^2 is an upper limit for targets with Be as backing material. The boundary conditions in these cases were: Vacuum on one side, a copper clamp ring at room temperature, and quasi-stagnant* 1 atm pressure He gas on the other side.

To further illustrate the seriousness of the present target limitations, it should be kept in mind that we have so far only considered light ions. If in the previous example the ^{18}O beam is changed to a ^{238}U beam (5.6 MeV/A) and all other conditions are kept the same, the power density in the target goes up to 810 W/cm^2 (a factor of 36!). Without improvements in present target technology, the U beam would have to be limited to 1.35×10^{11} particles per second. The goal was therefore to design a target system which will allow a significant increase in beam intensity.

* Quasi-stagnant is defined as He gas flowing at a rate of $40 \text{ std cm}^3/\text{sec}$ through a chamber located behind the target. The center of the stream was 20 mm away from the target.

B. The New Target System

1. The Operating Principle

The operating principle of the new target system can best be understood by referring to Fig. 1. The conventional single target which also acted as a window to separate the recoil stopping gas from the machine vacuum is replaced by a double window. A similar arrangement is used for the exit of the beam. A high velocity gas stream passes between each of the two foils and removes the heat generated by the beam in the entrance and exit windows, the gas itself, the target backing, and the target. It is important to realize that the differential pressure across the target can be made zero if the cooling gas has the same pressure as the stopping gas. This greatly reduces mechanical stress on delicate targets. Even a slight "leak" in the target is of no consequence if the cooling and stopping gas are of the same species (in general He). In the following, some theoretical considerations for the design of such a gas cooling system shall be given.

2. Theoretical Considerations

The heat transfer between a wall and a gas can be described by equation (1).

$$P = \alpha \cdot F \cdot \Delta T \quad (1)$$

Here P is the power transferred, α is the heat transfer coefficient, F the area of contact, and ΔT the temperature difference between the wall and the gas.

The following implicit expression for the film heat transfer coefficient α has been found empirically (Ref. 3):

$$Nu = \text{const.} (Re)^{0.8} \cdot (Pr)^{0.3} \quad (2)$$

Here Nu is the Nusselt number, Re the Reynolds number, and Pr the Prandtl number. This equation holds for turbulent flow and $Re \gtrsim 10,000$.

Nu, Re, and Pr are dimensionless, and defined as follows:

$$Nu = \frac{\alpha \cdot \ell}{\lambda}$$

$$Re = \frac{\rho \cdot v \cdot \ell}{\eta}$$

$$Pr = \frac{\eta}{\rho \cdot a}$$

with ℓ characteristic length, λ thermal conductivity of the gas, ρ density, v velocity, η kinematic viscosity, a temperature conductivity.

Pr can also be calculated from the ratio of the specific heats, $\gamma = c_p/c_v$:

$$Pr = \frac{4}{9 - (5/\gamma)}$$

The film transfer coefficient can therefore be written as

$$\alpha = \text{const.} \frac{\lambda}{\ell} (Re)^{0.8} \cdot (Pr)^{0.3} \quad (3)$$

This expression has been found valid for a wide range of Reynolds numbers from 10^3 to 3×10^5 using flow through tubes with circular cross sections (Ref. 3). Particularly good agreement is obtained when the quantities Re, Nu, and Pr are evaluated at the film temperature which is defined as

$$T_f = \frac{1}{2} (T_w + T_b) \quad (4)$$

This is the average temperature between the wall (T_w) and the bulk of

the gas (T_b). Eq. 3 can also be used for noncircular cross sections if the characteristic length in the Reynolds number is expressed as

$$\ell = \frac{4A}{U}$$

where A is the area, and U the circumference of the cross section (Ref.

4). Thus, the expression for the Reynolds number becomes

$$Re = \frac{4 \cdot \rho \cdot v \cdot A}{U \cdot \eta} \quad (5)$$

The product $\rho \cdot v \cdot A$ corresponds to a mass flow $\dot{m}$; with this we have

$$Re = \frac{4\dot{m}}{U \cdot \eta} \quad (6)$$

It has to be emphasized that the above treatment of heat transfer is only an approximation for the following reasons:

- (a) The temperature of the wall (window, target) is not constant; it is rather a two-dimensional distribution which itself is dependent on the cooling mechanism.
- (b) The cooling gas flow across the target/windows is purposely made nonuniform, with the highest flow in the center, diminishing to zero at the edges, when edge cooling takes over.
- (c) The temperature gradient between the wall and the gas can be as high as 700°K and the simple averaging procedure of Eq. 4 has to be reexamined in view of the fact that ρ , λ , and η are temperature dependent.
- (d) The flow conditions in the double window are not known. "Anlauf"-phenomena and normal components to the assumed longitudinal flow are not considered here.

Keeping these restrictions in mind, the above expressions can, however, be used to determine the conditions under which maximum cooling can be achieved.

A figure of merit, μ , can be derived from the expression for the heat transfer coefficient α , Eq. (3). If Re is evaluated according to Eq. (5), μ can be defined as:

$$\mu = \lambda \left(\frac{\rho}{\eta}\right)^{0.8} \cdot (Pr)^{0.3} \quad (7)$$

Using SI units throughout and assuming a gas temperature of 300°K, Table I gives the values of μ for different gases. It is now obvious that hydrogen is the best candidate for a cooling gas, with He as a second choice.

Table I also contains the figure of merit for He, H₂, and Ne at 77.3°K. The increased density and lower viscosity gives rise to higher Reynolds numbers. This results in higher figures of merit even though the thermal conductivity is reduced. Lower cooling gas temperatures were, therefore, part of the experimental investigation.

C. The Design

1. The Target Block

Fig. 2 shows an artist's view of the final design of the High Intensity Heavy-Ion Target System.

The beam enters through a collimator and a beam monitor foil. It then encounters the gas-cooled, dual-foil, entrance window. The target material is deposited on the backside of the second foil. The beam traverses the recoil stopping chamber and leaves the HIHIT through the gas-cooled dual foil exit window. It continues from there to the faraday cup. The following details are worth mentioning:

- The target block can be surrounded by liquid nitrogen to give effective edge cooling and to cool the recoil stopping gas.
- Four (instead of the conventional one) capillaries are used to collect the recoils. This allows a certain amount of recoil range discrimination for different reaction mechanisms.
- A scattering channel at 30° with respect to the beam direction allows the observation of scattered beam particles and the continuous monitoring of the beam energy.
- An infrared television channel "looks" at the target at an angle of 30° .
- A third channel containing an infrared emitting diode "illuminates" the target from above.

2. Details of the Construction

a. The Gaskets. As outlined in Section B2, it is desirable to have the capability of operating at low cooling gas temperatures. We have taken as a practical lower limit 77°K (liquid nitrogen (LN)). Since no suitable gasket for these temperatures could be found on the market, we have developed our own indium-copper gasket, shown schematically in Fig. 3. The drawing is self-explanatory except for the following points:

- The retainer ring limits the compression of the gasket.
- The retainer ring centers the gasket and its reuse is unlimited. (A spent gasket can be "popped" out under slight pressure.)
- The surfaces to be sealed by the gasket are flat and do not have to line up radially. Any damage to these surfaces (scratches, etc.) can be repaired easily and practically an unlimited number of times.
- The gasket requires only slightly higher sealing pressure than an o-ring; it has been tested for operation between 77°K and 350°K .
- It is inexpensive, and in some cases the copper has been reused several times with a new indium-alloy coating.

b. The Windows. Fig. 4 shows the details of the front window, the target, and the cooling gas channel. A difficult mechanical problem is the vacuum-tight attachment of the thin foil (which forms

the entrance window) to the window frame. A metal gasket cannot be used for this purpose because of the fragility of some foils (example: Be). Ultrasonic soldering is successful only for a limited number of materials, and elastomer seals leak at low temperatures. We have therefore developed a gluing technique which has worked for the temperature range from 77°K to 400°K for the following materials: Be, Al, Ni, Ti, Mo, and HAVAR. The process is based on a cyanoacrylate glue (LOCTITE adhesive No. 317, with primer T). The surfaces to be joined are sand-blasted and ultrasonically cleaned; the primer is applied to both surfaces and dried. The surfaces are joined together with a small amount of adhesive and cured under pressure for 20 minutes at 100°C. The target and the exit window are glued in a similar fashion. All windows on which tests were performed and reported in this paper had the same diameter of 9.5 mm.

c. The Gas Diffusor. The purpose of the gas diffusor and its two caps (Fig. 4) is to direct the cooling gas towards the window and the target, and to distribute the flow so that the central portions receive maximum mass flow. Near the edge of the window/target, the flow actually drops to zero, because edge cooling can be relied upon as the dominant cooling mode. The specific mass flow (unit: mass/time/area) as a function of vertical displacement X follows a $K \cdot \sin X$ function with X ranging from 0 to π . This, however, seriously complicates exact calculations of the cooling process.

3. The IR-TV System

a. Optics. In a previous experiment (Ref. 2), an infrared detector was used successfully to monitor the integral temperature of the target and to protect it electronically from being destroyed by too high a beam intensity. Going one step further, an IR-TV system was built which allows optical inspection of the target while it is being irradiated by the beam. The target is imaged with two achromats onto the end of a coherent fiber optics bundle which is connected via a relay lens to an infrared-sensitive television camera. An infrared filter (Hoya: IR-80, $\lambda 5 < 730 \text{ nm}$, $\lambda 80 > 900 \text{ nm}$) is used to block out visible light which is generated when the beam traverses the stopping gas.

The television camera is a conventional unit which has been equipped with an infrared vidicon with a silicon-target diode mosaic (RCA 4825). The response function of this photoconductor is shown in Fig. 5. Since the cutoff wavelength for the vidicon is shorter than "ordinary" glass, no special IR-transmitting components are necessary for lenses, windows, or optical fibers. The fiber-optics bundle has 80,000 fibers of 10 μm diameter, and its resolution is matched to the resolution of the TV camera.

Optical inspection of the target during an experiment is desirable to check for flaking, warpage and any change in surface structure. If the target is too cold, however, to be visible in its own light, a small infrared emitting diode can be used for illumination (cf. Fig. 2).

b. Electronics. The video signal from the television camera contains the temperature information for the whole target. When suitably

processed, it can be used to protect the target from being overheated by the beam. This is accomplished by the electronic device shown schematically in Fig. 6. The video signal enters a horizontal and vertical synchronization separator. A vertical and horizontal gate signal are developed which open a series/shunt gate so as to let only the central portion of the picture pass. A level detector "looks" at this gated video signal and fires whenever its amplitude exceeds a preset value. The rationale for the gating circuit is that the video signal contains high amplitude components at the beginning and end of each line as well as on the top and bottom of the picture. Unless blocked out, these signals would be interpreted as "hot spots" on the target. To indicate directly on the TV screen that the level detector has fired, a shunt gate is activated which blocks the "hot" portion of the picture. The output of the level detector also interrupts the accelerator beam. It will be explained in the next section how a precise correlation between target temperature and detector level was obtained. Some modifications of the TV camera were necessary to assure that under the condition of complete darkness uniform noise triggering of the level detector occurred over the entire sensitive area of the picture.

D. The Calibration Procedure

To obtain a calibration for the amplitude of the video signal as a function of target temperature, the target was replaced by an electrically-heated metal strip. The temperature of the strip was measured by a thermocouple. The video signal amplitude was then determined by adjusting the level-detector setting to the point where it started firing. Fig. 7 shows the calibration curves obtained this way for different f-stops of the TV camera.* These curves were used in all subsequent measurements to determine the target temperature. The lower detection limit of the present system is 390°C.

* The automatic gain control of the camera was deactivated and the IR-filter was in place.

E. The Gas Circulator

The large amount of gas passing between the double windows (up to 10 kg/hr) makes it mandatory to have a closed gas-circulating system, as shown schematically in Fig. 8. The compressor receives warm gas from the heat exchanger and compresses it. The gas arrives through an oil separator, several filters, and a dryer at the supply regulator, the main function of which is to protect the front and back window from excessive pressure. In the cooling mode, the gas follows the black arrows, going through two flow meters, a heat exchanger, and a cooling coil submerged in LN before arriving at the target. From there, the slightly warmer gas returns to the heat exchanger, followed by a particle filter and a back-pressure regulator. The function of the back-pressure regulator is to maintain a sufficient pressure in the space between the target and the front window; so that the differential pressure between this space and the recoil chamber remains constant or zero.

In the warm-up cycle, the gas follows the white arrows: it passes through a heater into the target and leaves through another heat exchanger, which warms the gas to the point where the back-pressure regulator does not freeze up.

The following details are worth noticing:

- The whole circulator can be evacuated via V1. This is particularly important before the system is charged with hydrogen.
- The extensive filtering after the compressor is necessary to prevent any oil from reaching the

target. The beam would crack the oil, resulting in carbon build-up, excessive beam absorption and thermal failure of the windows and the target. The second purpose of the filters is to prevent small particles from being accelerated by the gas stream. These particles act as "micrometeorites" and put pinholes in the windows, with sometimes disastrous consequences.

- An electrically heated dummy target can be valved into the circuit by closing V7 and V9 and opening V8. This allows a determination of the total cooling capacity of the system.
- The particle filter in the return line prevents a broken radioactive target from contaminating the entire circulator system.

F. Experimental Results with the Electron Gun

1. Mechanical Properties of the Windows

A 6 kW/20 kV electron gun was used to simulate the heavy ion beam. It was equipped with a fast deflection system to obtain a pulsed beam. Since the beam spot was smaller (3.18 mm) than the target (9.53 mm), a wobble system was employed during most measurements, which resulted in a uniform illumination of the target by the electrons. Care was taken to measure the secondary electron emission for each window material, and suitable corrections were applied in calculating the beam power. The range of 20 keV electrons is 0.76 mg/cm^2 , which implies that all electrons are stopped in the front window and never reach the target. All e-gun measurements were, therefore, performed on the front window with a pyrex membrane in place of the target; so that the IR camera could be used to measure the temperature distribution. The goal of the measurements was to find the optimum cooling conditions by varying the following parameters:

- The window material
- The nature of the cooling gas
- The gas flow
- The gas temperature.

The selection of the window materials was largely based on experience gathered during several years of experiments with heavy-ion beams. To evaluate unknown materials, however, a figure of merit (F) for the usefulness of metal foils as beam windows was defined in the following way:

$$F = \frac{P_r \cdot D}{\Delta E} \quad (8)$$

Here P_r is the bursting pressure, D the diameter, and ΔE the energy loss in the window. Expressing ΔE in terms of material thickness σ and stopping power $dE/d\sigma$ gives

$$F = \frac{P_r \cdot D}{\sigma \cdot dE/d\sigma} \quad (9)$$

σ is proportional to the density (ρ) and the thickness of the foil (d), so that the expression for the figure of merit becomes:

$$F = P_r \cdot \frac{1}{\rho \cdot dE/d\sigma} \cdot \frac{D}{d} \quad (10)$$

This formula is used where the bursting pressure of a window has been measured. To evaluate unknown materials, the bursting pressure can be calculated from the following expression (Ref. 5):

$$P_r = 7.270 \cdot \tau^{3/2} \cdot \epsilon^{-1/2} \cdot d/D \quad (11)$$

Here τ is the tensile strength of the material and ϵ the modulus of elasticity. Substituting (11) into (10) gives

$$F = \frac{7.27 \times 10^{-3} \tau^{3/2} \cdot \epsilon^{-1/2}}{\rho \cdot dE/d\sigma} \quad (12)*$$

The units used in evaluating formulae (10) through (12) are:

P_r in kPa

ρ in g/cm³

$dE/d\sigma$ in MeV/mg/cm²

ϵ, τ in pascal ($\equiv$ N/m²)

* The numerical factor in Eq. 12 is necessary to obtain F values consistent with Eq. 10.

F-values for different materials are calculated in Column 9 and 11 of Table II for ^{19}F and ^{40}Ar beams of 6 MeV/nucleon energy and at 20°C operating temperature. Table II also includes calculated values for P_r for comparison with the experimental values. The principal uncertainty in these calculations is the values for the tensile strength. In cases where these are well known (example: HAVAR), good agreement between calculation and experiment is obtained. Bulk tensile strength values are of little value and give burst pressures which are almost always too low. The metallurgical history of the foil is of paramount importance for obtaining the correct tensile strength.

2. Time Constants of the Windows

The rise time for the temperature of a foil is arbitrarily defined as the time from turning on the beam until the foil reaches 90% of its final temperature. This is measured by observing the IR-camera video signal, which scans the full target once every 16.7 ms. The peak amplitudes of this signal are then translated into temperature values using the calibration curves, Fig. 7. An example of such a measurement is given in Fig. 9. This is a beam of 3.2 mm diameter on a molybdenum foil of 9.5 mm diameter (no wobble). The thickness of the foil is $3.76\text{ }\mu\text{m}$ with vacuum on both sides and the foil folder at room temperature. Fig. 10 shows the video signal from Fig. 9 translated into temperatures. The measured rise time is 210 milliseconds. The rate of rise, dT/dt , is 2380°K/sec , at a beam power of 6.7 W.

The cooling-down time of the foil to 10% of the maximum temperature can not be measured because the infrared vidicon does not register

surface temperatures in the range of 75°C . However, the temperature decrease during the first 16.7 ms after beam turn off was measured and corresponds to a rate of fall ($-dT/dt$) of 2990°K/sec .

A similar measurement was made while cooling the same window with He-gas at a beam power of 81 W. The rise time $t_{90\%}$ was 110 ms, and the rate of rise dT/dt equals 5870°K/sec . The rate of fall during the first 16.7 ms was surprisingly slow: $-dT/dt = 3540^{\circ}\text{K/sec}$.

3. The Cooling Power as a Function of Gas Flow

For the measurement of the cooling power versus gas flow, the temperature of the foil was kept constant by observing the video signal. It was then determined how much beam power was necessary to achieve this temperature for a given gas flow. The experiment was carried out with a HAVAR window of 9.5 mm diameter, $3.9\text{ }\mu\text{m}$ thick. A wobbled DC beam was used and the temperature in the center of the foil was kept at 500°C . The cooling gas was He at room temperature.

Fig. 11 shows the result of the measurement. A linear, least-squares fit leads to the relation:

$$N = 14.38 \times 10^4 \phi + 36.1 \quad (13)$$

The beam power (N) is measured in watts and the gas flow ϕ in kg/s.

Some experiments are done with windows or targets which have vacuum on one or both sides. We have, therefore, measured $T(\phi)$ for a molybdenum foil under these conditions. Fig. 12 shows the result. For vacuum on both sides and 500°C , the power density is 15 W/cm^2 ; for stagnant He on one side, it is 23 W/cm^2 at 500°C . These values agree well with those obtained with heavy-ion beams (cf. Section A). Fig. 12

also includes a special test with a 13 μm thick Be window (9.5 mm diameter) with vacuum on one side and stagnant argon on the other.

4. Window Temperature as a Function of Window Material

A simple calculation shows that, even for a window material of high thermal conductivity like beryllium, thermal conduction to the window holder plays only a small role in the cooling process at high beam intensities. To verify this experimentally, three windows made from 13 μm thick Be, 6 μm thick Ti, and 3.9 μm thick Mo were tested under conditions of different cooling gases (He and H_2) and temperatures (77°K and 290°K). Fig. 13 shows the result. Within the uncertainty determined by the scatter of the experimental points, no influence of the window material on the cooling process can be found, even though the three materials have widely differing thermal conductivities (Be:Mo:Ti = 9.7:6.2:1).

5. Pulsed versus DC Beams

In the past it was sometimes thought that pulsed beams are a considerable disadvantage when high average beam intensities are desired, the reasoning being that the time constant of the thin foils is so short that the peak beam current determines the maximum temperature. The surprisingly long time constant reported in Chapter G2, however, indicated already that this might not be too serious an effect. We, therefore, tested a 3.9 μm thick Mo window (9.5 cm diameter) with a DC beam and a pulsed beam of 36 Hz repetition frequency (the same as at the SuperHilac) and 50% duty factor. The average beam power was the

same in both cases. Fig. 14 shows at low power levels a small difference in favor of the pulsed beam (!). This deviation is too small to speculate about a possible explanation. We have not yet tested windows with more extreme duty factors.

6. Evaluation of Different Cooling Gas Temperatures

Fig. 15 shows a comparison of a Mo window cooled with He gas at room temperature and at 77°K. Due to the lower viscosity, the flow in the 77°K experiment was higher (5.35×10^{-4} kg/s) than in the room temperature experiment (2.99×10^{-4} kg/s). Using the formula (13) derived from Fig. 11, the ratio (N_{77}/N_{290}), of the beam power values for the cold and the warm He gas, which is necessary to heat the foil to a given temperature (500°C), can be calculated. This ratio is 1.43. The ratio of the heat transfer coefficients for this case was calculated to 1.41, using Eq. (3). Both values are in good agreement; the experimentally observed, however, is only 1.23 (at 500°C). This indicates that the increased heat carrying capacity due to the lower initial temperature cannot contribute significantly to the cooling process. This observation was confirmed for the case of H₂ at 77°K and 290°K (Fig. 15). The beam power to achieve 500°C foil temperature is 180 W in the case of room temperature H₂ gas and 198 W for 77°K H₂ gas. If these values are, however, corrected for the higher flow at the lower temperature (assuming a linear dependence between beam power and gas flow), the power levels became essentially identical (180 W and 185 W).

7. Different Cooling Gases

Three different gases, H_2 , He, and Ne, were compared in their cooling efficiency at $77^\circ K$ using a HAVAR window of $3.9 \mu m$ thickness. The resulting $T(N)$ curves are reproduced in Fig. 16. It was shown in the previous section that the cooling process is not limited by the heat capacity of the cooling gas. It should, therefore, be possible to interpret Fig. 16 in terms of the differences in heat transfer coefficients keeping in mind the restrictions mentioned in Section B2. Recalling Eqs. (3) and (6) and eliminating all temperature independent factors and constants, the heat transfer coefficient α becomes proportional to α^* .

$$\alpha^* = \lambda \left(\frac{\dot{m}}{\eta} \right)^{.8} (Pr)^{.3} \quad (14)$$

As pointed out in Chapter 2, the best agreement between Eq. 14 and experimental values is obtained when the heat transfer parameters are evaluated at the film temperature T_f defined by Eq. (4). With LN cooled gas and $500^\circ C$ for the hottest point of the window, T_f is approximately $100^\circ C$. Table III shows the values of the different parameters and of α^* for the three gases at $100^\circ C$. It also lists the calculated ratios $\alpha^*/\alpha^*(H_2)$ for He and Ne. These ratios compare favorably with the experimental values, which were calculated from Fig. 16 according to

$$\left[\frac{\alpha^*(He)}{\alpha^*(H_2)} \right]_{exp} = \frac{N^{500^\circ C} (He)}{N^{500^\circ C} (H_2)} = \frac{126}{198} = .64$$

$$\text{and } \frac{\alpha^* (\text{Ne})}{\alpha^* (\text{H}_2)}_{\text{exp}} = \frac{N^{500^\circ\text{C}} (\text{Ne})}{N^{500^\circ\text{C}} (\text{H}_2)} = \frac{70}{198} = .35$$

8. Cooling Efficiency

a. During an experiment which used a 13 μm Be window and H_2 gas at 77.3°K, the temperature difference of the cooling gas at the inlet and outlet side of the dual window system was measured. This allows a comparison between beam power and cooling power. The cooling power is calculated from

$$Q = c_p \cdot \dot{m} \cdot \Delta T \quad (15)$$

with $c_p (77^\circ\text{K}) = 1.08 \times 10^4 \text{ WS/kg}^\circ\text{K}$, $\dot{m} = 5.47 \times 10^{-4} \text{ kg/sec}$, and $\Delta T = 25^\circ\text{K}$, Q becomes 148 W. The beam power was 181 W. The additional cooling of 33 W plus losses can be accounted for by the fact that the LN cooling jacket was in operation.

b. In a second experiment the total cooling efficiency was determined. At a beam power of 230 W (H_2 cooling gas), the consumption of liquid nitrogen was 16 l/hr. The power necessary to evaporate 1 l LN per hour is 44.8 W; so that the total cooling power was $16 \cdot 44.8 = 717 \text{ W}$. This results in an overall efficiency of 32% and includes the losses in the heat exchanger, several uninsulated lines in air at LN-temperature and losses by conduction.

c. In a third experiment the maximum capabilities of the system were tested. By increasing the supply pressure of the cooling gas (H_2), a total throughput through the front window of $6.7 \times 10^{-4} \text{ kg/sec}$

was achieved at 77.3°K. At a beam power of 390 W, the temperature of the Mo window (3.76 μm thick, 9.5 mm diameter) reached 700°C. This corresponds to a power density of 550 W/cm² (!). The window showed no signs of deterioration after several hours of running.

G. Additional Observations

The following somewhat unrelated observations are worth communicating:

(1) Using hydrogen as a cooling gas at elevated window temperatures can give rise to the formation of hydrides and eventual failure of the window; though we have not observed any problems with HAVAR or Mo windows up to 700°C and Be up to 550°C. From our observations we established that an upper limit for the diffusion of H₂ through these windows at these temperatures is about 10⁻⁴ Torr l/sec. Information about metalhydrides can be found in Ref. 6.

(2) Even though the windows were uniformly illuminated by the electron beam, the temperature distribution across the foil in the direction of the gas flow was nonsymmetrical: The hottest spot of the window was always displaced downstream from the center. The obvious explanation is that the gas heated up as it moved along the window and was, therefore, less effective in cooling the downstream portion. We have successfully compensated for this by a nonuniform beam wobble; i.e., a wobble where the beam spends a longer time on the upstream portion.

(3) One of the reasons for developing a target system which can operate at LN temperature was the observation by ÄYSTÖ et al. (Ref. 7) that it is possible to operate a He-transport capillary system at this temperature without aerosols and still obtain good transport yields. Since aerosols on the detector end are a nuisance in many experiments, we plan to investigate this mode of operation.

(4) It is apparent from Fig. 8 that the gas circulator is a complicated and expensive piece of equipment. If the ultimate cooling power is not needed, the following "economy" version of the gas cooling principle might be of interest: Room temperature N_2 gas is bubbled through LN and the cold gas used to cool the windows. The next stage of refinement would be to use the exiting gas to precool the room temperature N_2 via a heat exchanger. Ref. 8 gives a comparison of the efficiency of cooling gas production via the immersed heater method, the continuous flow-, and the bubbling gas-method.

H. Preliminary Observations with a Heavy-Ion Beam

As of now, the target has not been tested with a sufficiently intense beam to study the limits of its capabilities. In a very brief experiment (1 hour!) with a 118 MeV $^{20}\text{Ne}^{+9}$ beam of $\leq 3 \mu\text{A}$ intensity, we were able to observe with the TV camera that light in the visible range of the spectrum is produced in the stopping gas (He) as well as on the target ($\text{Mo } 4.49 \text{ mg/cm}^2$). This was expected since we are essentially performing a beam foil spectroscopy experiment. The light intensity from the target surface was much stronger than from the gas. However, both effects disappeared when the IR-filter was put in the optical path of the camera, and by reducing the cooling gas flow to zero the heating of the target by this weak beam was observed. These tests will be continued when the SuperHilac resumes operation.

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Table Captions

Table I: Figure of merit μ for gas cooling using different gases and temperatures.

Table II: Mechanical parameters and figure of merit for different window materials.

Table III: Heat transfer parameter α^* for different gases at 373°K .

	Gas	H ₂	He	Ne	N ₂	Ar	H ₂	He	Ne
	Unit	300°K	300°K	300°K	300°K	300°K	77.3°K	77.3°K	77.3°K
λ	W/m °K	.182	.152	4.93×10^{-2}	2.61×10^{-2}	1.86×10^{-2}	5.50×10^{-2}	6.28×10^{-2}	1.92×10^{-2}
ρ	kg/m ³	.0819	.163	.820	1.139	1.622	.318	.632	3.18
η	Ws ² /m ³	8.97×10^{-6}	20.1×10^{-6}	31.8×10^{-6}	17.9×10^{-6}	20.7×10^{-6}	3.61×10^{-6}	8.36×10^{-6}	12.2×10^{-6}
Pr	1	.707	.689	.663	.715	.636	.715	.690	.657
μ	(SI)	241	182	148	165	133	449	449	364

Table I

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TABLE II

Column #	1	2	3	4	5	6	7	8	9	10	11	12
Parameter	Material	Thickness	Rupture Pressure (exp.)	Tensile Strength	Modulus of Elasticity	Rupture Pressure (calc.)	$\frac{Pr \cdot D}{\rho \cdot d}$	Fluorine ¹²⁾ Stopping Power	Fluorine Figure of Merit	Argon Stopping Power	Argon Figure of Merit	Reference
Unit	--	μm	kPa	MPa	10^{10} Pa	kPa	$\frac{\text{m}^4}{\text{s}^2}$	MeV/mg/cm ²	--	MeV/mg/cm ²	--	--
Symbol	--	d	P_r^{exp}	τ	ϵ	P_r^{calc}	--	dE/d σ	F_{Fluorine}	dE/d σ	F_{Argon}	--
	Al-1145-0	25	60	67	7.1	7.48	4.44	3.82	1.16	11.3	.39	9
	Al-1145-H19	25	160	190		35.7	11.85		3.10		1.05	9
	Al-5052-0	25	185	193		36.5	13.7		3.58		1.21	9
	HAVAR	13	425	1793 to 2413	20.69	645	20.48	3.15	6.5	9.3	2.20	9
	HAVAR	13	450			to 1007	14.15		4.49		1.52	10
	HAVAR	13	920				20.84		6.61		2.24	11
	Ta	7.47	480	689 to 1130	18.6	485 to 1018	1.82	1.97	.92	5.8	.31	11
	Ta	5	380			254 to 534	2.75		1.39		.47	10
	Ta	2.5	315			127 to 166	4.55		2.31		.79	10
	Mo	4	215	837 to 1207	32.4	228 to 357	3.16	2.69	1.17	8.0	.40	10
	Mo	3	175			171 to 268	3.43		1.27		.43	10
	Ti	4	300	234 to 557	10.7	53	9.91	3.41	2.9	10.1	.98	10
	Nb	4	215	341	10.5	94	3.77	2.69	1.4	8.0	.47	10
	Ni	2.5	(100)*	470	20.0	41.4	4.49	3.15	1.42	9.3	.48	--
	Be	14.6	586	≥ 270	30.6	60	20.71	4.37	4.77	130.0	1.59	--
	W	--	--	~ 4200	38.6	--	--	1.97	8.39	5.59	2.96	--

*Estimated value

Parameter	η	λ	Pr	$\dot{m}$	α^*	$\frac{\alpha^*}{\alpha^*(H_2)}$ calc.	$\frac{\alpha^*}{\alpha^*(H_2)}$ exp.
Unit	(Ws ² /m ³)	(W/m °K)	(1)	(Kg/s)	(SI)	(1)	(1)
He	22.8×10^{-6}	.174	.69	7.70×10^{-4}	2.60	.81	.64
H ₂	10.6×10^{-6}	.222	.70	3.39×10^{-4}	3.17	/	/
Ne	36.5×10^{-6}	.0557	.66	20.9×10^{-4}	1.25	.39	.35

TABLE: III

Figure Captions

- Fig. 1. The operating principle of the gas-cooled target system.
- Fig. 2. Artist's view of the high intensity heavy-ion target.
- Fig. 3. Schematic view of the indium metal gasket.
- Fig. 4. Exploded view of the front window and the target.
- Fig. 5. Response function of the IR-vidicon photoconductor.
- Fig. 6. Schematic diagram of the video processor.
- Fig. 7. Calibration curves for the IR-discriminator level versus temperature for different F stops.
- Fig. 8. Schematic diagram of the gas circulating-, cooling-, and purifying system.
- Fig. 9. Oscillographic registration of the IR-video signal $V(t)$ during a beam pulse.
- Fig. 10. Video signal $V(t)$ from Fig. 9 translated into temperature $T(t)$.
- Fig. 11. Flow Φ as a function of beam power N for a constant window temperature of 500°C (cooling gas: He at 293°C ; window material: HAVAR, 9.5 mm diameter, $3.9\text{ }\mu\text{m}$ thick, DC beam).
- Fig. 12. $T(N)$ for a Mo-window (9.5 mm diameter, $3.8\text{ }\mu\text{m}$ thick) with stagnant gas or vacuum on one side and vacuum on the other.
- Fig. 13. Comparison of different window materials under different cooling conditions. (All windows have 9.5 mm diameter.)
- Fig. 14. Comparison between a DC- and pulsed beam of the same average power. (Mo-window $3.9\text{ }\mu\text{m}$ thick.)

Fig. 15. Evaluation of different cooling gas temperatures.

Fig. 16. Comparison of different cooling gases at 77°K.

Fig. 1

Fig. 2

XBL 757-3640

XBL 764-2615

Fig. 3

CRYO TARGET ASSEMBLY

TARGET ASSEMBLY

XBL 757-3639

Fig. 4

XBL 764-2607

Fig. 5

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Fig. 6

XBL 764-2616

XBL 764-2601

Fig. 7

XBL 757-3455

Fig. 8

XBB 764-3370

Fig. 9

XBL 764-2611

Fig. 10

XBL 764-2602

Fig. 11

XBL 764-2600

Fig. 12

XBL 764-2608

Fig. 13

XBL 764-2599

Fig. 14

XBL 764-2610

Fig. 15

XBL 764-2609

Fig. 16

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