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An isopropanol-solid carbon dioxide cooled accelerator target assembly

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An isopropanol–solid carbon dioxide cooled accelerator target assembly

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Abstract An efficient accelerator target assembly and cooling system is described. The target assembly consists of a cooled copper jacket with interchangeable targets. The cooling system employs an isopropanol–solid carbon dioxide cooling bath and isopropanol as the coolant. The system is an improvement over conventional water-cooled assemblies and has the advantages of eliminating the need for deionization of the coolant, providing cooling to near 200 K in thick targets, and allowing operation at much higher beam power loadings in thin targets. The target design was evaluated with an electron beam in aluminium and tantalum targets up to power loadings of 2 kW cm^{-2}.

1 Introduction

Conventional water cooled accelerator targets and beam windows are frequently unsuitable or disadvantageous for many research applications of electron and particle accelerators. Some of these applications are: (i) when accurate beam current measurement or integration from the window or target is required; (ii) when a one-thickness thin window with no backing is needed; (iii) when a small, well defined, unscanned beam spot at a high total beam power loading is desired. The conventional assemblies, using chilled water as coolant, are often undesirable for beam current measurement because of the inherent difficulties associated with the good electrical conductivity and solvent properties of water.

Water-cooled thick targets, such as high energy bremsstrahlung radiators, are usually adequate when provided with good demineralization since the cooling water ordinarily flows directly through or behind the target. A typical water-cooled thick target bremsstrahlung radiator, based on the design calculations of J Baglin *et al.* (1967 private communication), was described by Weisfield (1970). Although these thick targets are satisfactory most beam windows and thin targets with no backing are not at high total beam-power loadings. These thin-windowed targets usually employ chilled water circulated in a jacket surrounding the window or target (High Voltage Engineering 1967 data sheets ED-1015, ED-1016, ED-1022). Unless demineralization is provided, the cooling system must be electrically isolated from the target, and this greatly decreases the cooling effectiveness. Even with the best of these systems, the cooling efficiency is limited by the relatively low cooling ability of water. Typical design calculations for water cooled targets (Starr 1964) indicate the need for more efficient cooling systems.

A target assembly and cooling system was designed to meet the requisites listed above and to eliminate some of the difficulties and inconveniences of conventional water cooled systems.

2 Details and design of the apparatus

2.1 *Target assembly*

The target assembly consists of a massive copper jacket in which the target foil is mounted between two copper plates. It was hoped that direct cooling of only the copper plates would provide effective cooling in the foil because of the excellent thermal conductivity of copper and the large surface area between the target foil and the copper plates. This would avoid having the coolant in direct contact with the target and thereby eliminate difficulties with seals during target changing or replacement. Secondly, with this design the coolant is not in the path of the beam as in most thick target designs where the coolant flows behind or through the target. The design therefore provides cooling for thick targets composed entirely of one homogeneous material.

In the following description of the target assembly, as shown

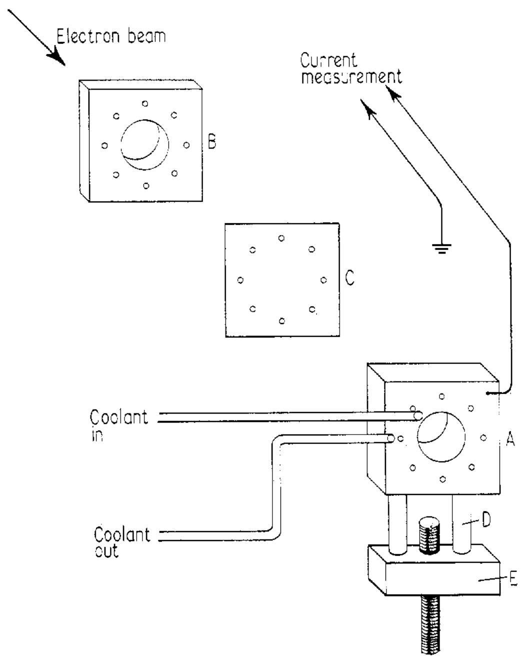

Figure 1 Target assembly: A, cooled copper plate; B, copper backing plate; C, target foil; D, ceramic stand-off posts; E, aluminium target supports

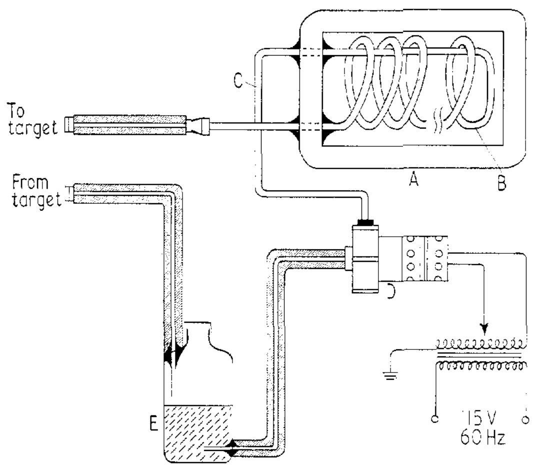

Figure 2 Cooling system: A, 30 l polystyrene cryostat; B, 10-turn copper coiling coil; C, 3/8 in i.d. copper tubing; D, magnetic drive circulating pump of polypropylene construction; E, 4 l polyethylene coolant reservoir; F, 1/4 in polyethylene tubing with 1 in rubber insulation, provided with 'Polyflo' fittings for connection to target assembly

in figure 1, metric dimensions are not used since the assembly was fabricated to meet standard American machining practices. Piece A consists of a 5 in × 5 in × 5/8 in copper block which contains a 3/8 in diameter spiral conduit with an internal volume of 13 cm^3. The target foil C was held in place using a 1/4 in copper plate B. Beam current measurement and monitoring from the metal target was possible since the entire assembly was mounted on two ceramic standoff posts D to electrically isolate the target from its aluminium support E.

2.2 *Cooling system*

Use of an organic solvent for cooling has certain clear advantages over water. Radiation damage to organic solvents results in only very short lived species, e.g. free radicals, which do not increase the conductivity of the coolant. This absence of long lived ionized products and the limited solubility of inorganic ions in organic solvents alleviates the problems associated with providing deionization. Proper selection of a suitable solvent also allows operation at temperatures below 273 K. Isopropanol was selected for its low electrical conductivity, low freezing point (183 K) and moderately high boiling point (355 K). Although several other alcohols also satisfy these requirements isopropanol was chosen since it is readily available in fairly pure condition at a reasonable cost.

The cooling system is shown in figure 2. A 30 litre polystyrene cryostat A fitted with a 10-turn copper coil B is used for cooling the isopropanol. The cooling bath in the cryostat is an isopropanol–solid CO_2 mixture used to maintain a temperature of 195 K. A slurry of 8 l of isopropanol and 12 kg of crushed solid CO_2 will provide cooling for over 36 hours of continuous use. A magnetic drive pump D circulates the coolant first through the copper coils in the bath and then to the target assembly. The magnetic drive pump of polypropylene construction has no seals to leak and the coolant contacts only the chemical resistant polypropylene. The pump was normally operated at flow rates of 5–20 l h^{-1}. A 4 l polyethylene coolant reservoir E, located after the target assembly, is used to allow evaporation or expansion of the coolant on heating in the target.

3 Experimental evaluation of the apparatus

3.1 *Experimental*

The target assembly and cooling system was evaluated using an electron beam from the RPI 3 MeV Van de Graaff (High Voltage Engineering model KS electron accelerator). The accelerator is mounted vertically and delivers a horizontal beam after a 90° deflection by a variable bending magnet. A linear electromagnetic quadrupole doublet lens (High Voltage Engineering model M-365) is used for focusing the beam before its exit from a 0·127 mm (5×10^{-3} in) aluminium window. Measurements on the target assembly were conducted outside the vacuum and adjacent to the aluminium window.

The energy of the electron beam was measured as the output of a generating voltmeter mounted on the high voltage terminal. The generating voltmeter was calibrated at 1·66 MeV using the photoneutron induced activity in silver (^{107}Ag (n, γ)^{108}Ag) through the ^{9}Be(γ, n) reaction. An Elcor model A308C current indicator and integrator was used to measure the electron beam current from target to ground. In the case of thin targets, the total current was measured by summing the current in the target foil and in a secondary iron target located behind the foil. The reported beam power P is given as the product of the measured electron energy E and the measured beam current I. The area of the beam spot, or cross-sectional area, was estimated by two methods. The first method was to measure the size of a burn spot on thin tantalum foils after irradiations at high currents. The diameter of these burn spots were found to be 2–3 mm corresponding to beam loading areas of 0·03–0·07 cm^2. The second method involved estimating the area of fluorescence on a quartz plate mounted at the window and observed on a closed-circuit TV monitor. The entire quartz plate fluoresced at higher currents and could only be used with currents below 1 μA. At low currents, it was found to be relatively constant with an area approximately 0·1 cm^2. The fluorescent area was not rigidly defined, and this value is probably greater than the true beam spot. The measured upper limit of 0·1 cm^2 was chosen, however, as the beam loading area and was assumed throughout. Therefore, the power per unit area, or beam power loading P_L, was assumed to be equal to $10P$ in units of power per cm^2.

Temperature measurements used to evaluate the cooling ability of the system were made with 30 gauge copper–constantan (40% Ni–60%Cu) thermocouples compared with a reference junction at 273 K. To ensure as accurate a monitor of temperature as possible, the thermocouples were mounted on the target foils very near to the beam spot, and calibrated in the mounted position using standard procedures (cf. Baker 1950).

Temperature measurements were made on cooled and uncooled targets. Thin targets, 9·25 μm ($0{\cdot}36 \times 10^{-3}$ in) aluminium and 25·4 μm (10^{-3} in) tantalum, were used to evaluate the use of the system as a beam window or thin bremsstrahlung radiator. A 6·35 mm (0·25 in) aluminum block was used to evaluate the efficiency for thick targets where the total energy of the electron beam is deposited. Irradiations of the various targets were carried out at electron energies of 2·0–2·4 MeV where the accelerator operation was most stable. During an irradiation at a given beam power loading, first a rapid increase in temperature was evidenced, followed by a slow establishment of an equilibrium temperature T_{eq} at which point the input heating rate from the electron beam is equal to the dissipation of heat from the target. The difference in temperature between this equilibrium point and the initial temperature T_i was measured as a function of the beam power loading.

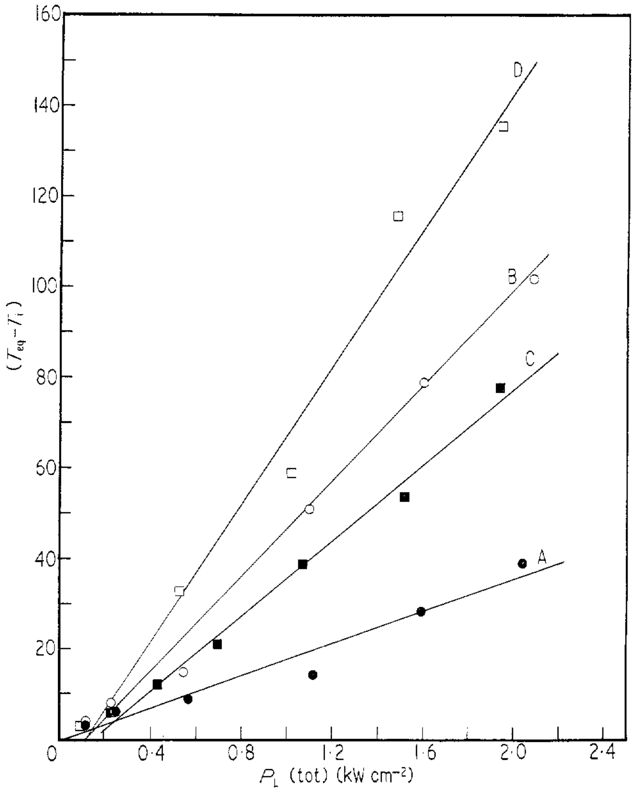

Figure 3 Temperature increases in aluminium targets as a function of the total electron beam power loading: A, for cooled 6·35 mm (0·25 in); B, for uncooled 6·35 mm (0·25 in); C, for cooled 9·25 μm (0·36 × 10^{-3} in); D, for uncooled 9·25 μm (0·36 × 10^{-3} in). Beam loading area approximately 0·1 cm^2

3.2 *Results*

Typical data for the heating $(T_{eq}-T_i)$ in aluminium targets as a function of the beam power loading are shown in figure 3. The wide scatter of data points is a result of experimental uncertainties in both the power and temperature measurements. Since the temperature increases appear to be linear in the beam power loading, the data of figure 3 were fitted with straight lines by a linear least squares analysis. The slopes of these lines, termed the heating rates, are beam power loading differentials of the temperature increase, i.e., $d(T_{eq}-T_i)/dP_L(\text{tot})$, and are used as the parameters to evaluate the cooling efficiency. These heating rates and the initial temperatures of the aluminium targets are listed in table 1. The reported errors for the heating rates are 2σ values obtained from the variance σ^2 of the slopes which where evaluated from the variance of the parent distribution in the least squares analysis.

Data for the heating in cooled thin aluminium and tantalum targets are provided in figure 4 and table 2. These data were treated in a similar manner as that above, except that the beam power used in the calculations was only that of the electron beam deposited in the foil. For these targets the total power loading $\{P_L(\text{tot})\}$ is approximately an order of magnitude larger than the target power loadings $\{P_L(\text{tgt})\}$ shown in figure 4. The straight line fits to the data of figures 3 and 4 were made because of their apparent linearity. No theoretical basis is implied. However, the slopes are indicative of the heating rate in each case. The positive intercept at zero target power loading for line A in figure 4 indicates an apparent anomaly in the formulism since the intercept would be expected to be zero. In the case of aluminium, this may be a result of measuring the heating $(T_{eq}-T_i)$ as a function of P_L(tgt) instead of P_L(tot). The exact functional dependence of the data, however, and the thermodynamics of the system are beyond the scope of this paper.

Table 1 Heating rates in aluminium targets using data of figure 3

Aluminium target	T_i (K)	$\frac{d}{dP_L(\text{tot})}(T_{eq}-T_i)$ (K cm^2 kW^{-1})
cooled 6·35 mm (0·25 in)	202	17·9 ± 4·3
uncooled 6·35 mm (0·25 in)	293	41·8 ± 4·2
cooled 9·25 μm (0·36 × 10^{-3} in)	271	52·9 ± 5·1
uncooled 9·25 μm (0·36 × 10^{-3} in)	294	76·8 ± 7·3

From the data, it is apparent that thick targets are cooled to much lower initial temperatures and have significantly lower heating rates than thin targets. The isopropanol–solid CO_2 cooled targets provide 30–60% more effective cooling than in uncooled targets as indicated by the percent differences in the heating rates. At a power loading of 2 kW cm^{-2}, the difference in equilibrium temperature between cooled and uncooled targets is 70 K for thin 0·36 × 10^{-3} in aluminium and 150 K for thick 0·25 in aluminium. Although the differences in heating rates and equilibrium temperatures between cooled and uncooled targets are significant, perhaps more so are the low absolute equilibrium temperatures of the isopropanol–solid

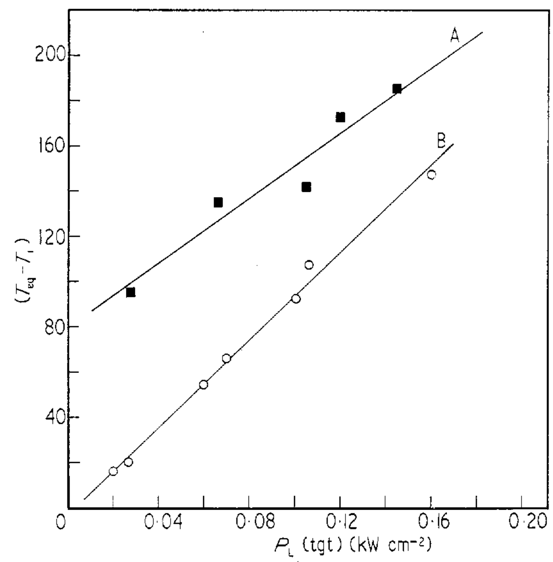

Figure 4 Temperature increases in cooled thin targets as a function of the power loading of the electron beam deposited in the foil: A, for 9·25 μm (0·36 × 10^{-3} in) aluminium; B, for 25·4 μm (10^{-3} in) tantalum. Beam loading area approximately 0·1 cm^2

Table 2 Heating rates in cooled thin aluminium and tantalum targets using data of figure 4

Target	T_i (K)	$\frac{d}{dP_L(\text{tgt})}(T_{eq}-T_i)$ (K cm^2 kW^{-1})
9·25 μm (0·36 × 10^{-3} in) aluminium	271	713 ± 18
25·4 μm (10^{-3} in) tantalum	273	965 ± 6

CO_2 cooled targets. In the thick 0·25 in aluminium at 2 kW cm^{-2} the absolute equilibrium temperature is only 238 K. These low equilibrium temperatures are important in that the target is always at a lower temperature than uncooled or water cooled targets and can thus be used at higher power loadings. For example, assuming that the temperature increases in water cooled targets of 0·25 in aluminium are similar to those of this system, the equilibrium temperature of the target would reach the boiling point of water at power loadings of 5·0 kW cm^{-2} compared to reaching the boiling point of isopropanol at 8·5 kW cm^{-2}.

4 Conclusions

The target assembly and cooling system described in this article is an improvement over most water cooled systems. The necessity for deionization is obviated by the use of isopropanol as the coolant. The isopropanol–solid CO_2 cooling system and the massive copper cooling jacket provides more efficient cooling and enables use of targets at much higher beam power loadings. Starting at temperatures near 200 K, heating rates of less than 20 K cm^2 kW^{-1} were evidenced in thick aluminium targets.

With minor revisions the target assembly could be used for applications not described in this paper, e.g. fast neutron production from low energy deuterons in tritiated titanium targets. The cooling system can be used without modification for most other target applications normally associated with charged particle beams.

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