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DEVELOPMENT OF A HIGH-HEAT-FLUX TARGET FOR MULTIMEGAWATT, MULTISECOND NEUTRAL BEAMS AT ORNL*

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Abstract

A high-heat-flux target has been developed for intercepting multimegawatt, multisecond neutral beam power at the Oak Ridge National Laboratory (ORNL). Water-cooled copper swirl tubes are used for the heat transfer medium; these tubes exhibit an enhancement in burnout heat flux over conventional axial-flow tubes. The target consists of 126 swirl tubes (each 0.95 cm in outside diameter with 0.16-cm-thick walls and ≈1 m long) arranged in a V-shape. Two arrays of parallel tubes inclined at an angle α to the beam axis form the V-shape, and this geometry reduces the surface heat flux by a factor of 1/sin α (for the present design, α = 13° and 21°). In tests with the ORNL long-pulse ion source (13- by 43-cm grid), the target has handled up to 3-MW, 30-s beam pulses with no deleterious effects. The peak power density was estimated at ≈15 kW/cm² normal to the beam axis (5.4 kW/cm² maximum on tube surfaces). The water flow rate through the target was 41.6 L/s (660 gpm) or 0.33 L/s (5.2 gpm) per tube (axial flow velocity = 11.6 m/s). The corresponding pressure drop across the target was 1.14 MPa (165 psi) with an inlet pressure of 1.45 MPa (210 psia). Data are also presented from backup experiments in which individual tubes were heated by a small ion source (10-cm-diam grid) to characterize tube performance. These results suggest that the target should handle peak power densities in the range 25–30 kW/cm² normal to the beam axis (≈10 kW/cm² maximum on tube surfaces) with the present flow parameters. This translates to beam power levels of 5–6 MW for equivalent beam optics.

Introduction

Along with the technology advances in neutral beam injection systems, it has been necessary to improve the power handling capability of the targets (or beam stops). The new generation of injectors is producing ion beams in the multimegawatt and multisecond regime. The ORNL long-pulse ion source[1] was designed to operate at high power (≈4 MW) for long pulses (30 s). For this application a steady-state target was required; the expected peak power densities normal to the beam axis were a few tens of kilowatts per square centimeter. Copper swirl tubes were chosen as the heat transfer surface since they appeared to be the most attractive candidate for enhancing the burnout heat flux. This enhancement is attributed to the vortex flow generated by a twisted tape swaged inside the tube (centrifugal forces displace the vapor blanket from the heated wall through buoyancy effects). Burnout experiments conducted by Gambill et al.[2–4] indicated a burnout heat flux a factor of 2 higher for swirl flow than for the axial-flow case. For beam stops, where the heat transfer is nonuniform azimuthally, the enhancement of burnout heat flux is expected to be even greater.

A target using swirl tubes has been fabricated at ORNL and tested with the ORNL long-pulse ion source. Some background information on swirl-flow heat transfer is discussed; design features and performance of the target are presented; and results from backup experiments in which individual test tubes were heated by a small ion source are described.

Background Swirl-Flow Heat Transfer

Gambill et al.[2–4] reported detailed studies on swirl flow, including experimental determinations of burnout heat fluxes, heat transfer coefficients, and friction factors for water flowing through electrically heated tubes containing Inconel twisted tapes. Burnout heat fluxes up to 4.4 kW/cm² for copper tubes and up to 12 kW/cm² for nickel tubes were mesured, depending upon the tube size, the pressure drop (or water velocity), the heated length, and the tape-twist ratio y. The ratio y is defined as the number of internal tube diameters per 180° twist for the tapes. The highest burnout fluxes were achieved in short test sections at very high pressure drops (or water velocities); for example, the burnout flux of 12 kW/cm² was obtained for a 3.8-cm-long nickel tube at a pressure drop of 2.92 MPa (423 psi) and an axial flow velocity of 45 m/s. In general, the burnout heat fluxes for swirl-flow tubes were found to be twice as large as those for straight axial flow through identical tubes without a twisted tape (compared at the same overall pumping power). Also, the burnout heat fluxes were found to be independent of both pressure level and degree of subcooling.

For forced convection in swirl tubes with twisted tapes (nonboiling flow regime), Gambill et al.[3,4] obtained the following simplified correlation for the average swirl-flow heat transfer coefficient h_s in terms of the tape-twist ratio y:

$$h_s/h_a = 2.18/y^{0.09} , \qquad (1)$$

where h_a is the axial-flow heat transfer coefficient. Values of y in the study ranged from ≈2 to 12. Similarly, the correlation of Lopina and Bergles[5] can be represented as

$$h_s/h_a = 2.26y^{-0.248} . \qquad (2)$$

Although the dependence on y differed in these investigations, both correlations indicate that the heat transfer coefficient for swirl flow is about a factor of 2 higher than that for axial flow. Several investigators[3–6] have presented correlations for swirl-flow friction factors that allow pressure drop estimates. The referenced correlations were found to be useful in design of the target.

Previously, Kim et al.[7,8] discussed heat transfer as applicable to neutral beam targets (papers presented at the sixth and seventh symposia in this series, 1975 and 1977). In Ref. 8, the authors concentrated on swirl-tube heat transfer and presented performance results of several swirl-tube targets used on neutral

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beam development facilities up to that time. In a recent experimental investigation by Thompson et al.,[9] advanced cooling concepts for neutral beam calorimeters are discussed. Burnout data are presented for tests on tubes equipped with different enhancement mechanisms, including swirl flow (generated by tangential injection) and internally finned tubes (about a 5° helix). In these experiments, a laser was used to direct power onto a test spot (size ≈ tube outer diameter). Significant improvements in the burnout heat flux were observed, with reported burnout fluxes up to almost 14 kW/cm² for both a molybdenum tube with swirl flow and an internally finned copper tube. For copper tubes with swirl flow, burnout fluxes up to ≈8.5 kW/cm² were measured; for smooth copper tubes, burnout fluxes as high as 7 kW/cm² were obtained. These higher burnout fluxes were observed at the higher water velocities (test range ≈ 5–21 m/s). It should be pointed out that the investigators measured higher burnout fluxes for the finned tubes when the hot spot was centered over the base of the fins as opposed to between fins. Differences in burnout heat fluxes of up to 50% were found between adjacent points.

Target Design

A schematic of the water-cooled target is shown in Fig. 1, and the device itself is pictured in Fig. 2. Swirl tubes constructed at ORNL of OFHC copper (0.95-cm OD and 0.16-cm wall thickness) are used for the heat transfer surface. The thin walls and high thermal conductivity of these tubes minimize the thermal gradient across the heated wall, which results in reduced thermal stresses. The tubes are equipped with twisted Inconel tapes (0.038-cm thick) on a tight tape-twist ratio ($y \approx 2$). The target consists of 126 swirl tubes, each ≈1 m long, arranged in a V-shape. Each half of the V-shape is formed by an array of 63 parallel tubes inclined at an angle α to the beam axis. As illustrated in Fig. 1, α is a constant 21° for one array of tubes; however, for the other array α changes abruptly from 21° to 13° near the apex of the target. These angles were chosen to facilitate fabrication and installation in the ORNL Medium Energy Test Facility. The bends in the tubing, especially at the ends, help to prevent the twisted tapes from breaking loose and moving inside the tubes, which caused problems in some previous targets.

In fabrication each swirl tube was hand brazed at the ends to copper plates using the staggered arrangement shown in Fig. 3. The copper plates were then bolted to 4-in. Sch 40 stainless steel pipes, which serve as the water manifolds (Figs. 1 and 2); neoprene O-rings provide for the water/vacuum seal. This design offers some distinct advantages: (1) tubes overlap each other with respect to the beam, thus creating a shadowing effect that minimizes the possibility of the beam shining through; (2) individual tubes or entire tube arrays can be replaced with relative ease; and (3) tubes are physically isolated from each other. The third item is particularly important due to the high surface-heat fluxes experienced by the tubes during neutral beam pulsing. The corresponding thermal gradients result in differential longitudinal growth, which causes the tubes to bend; if the tubes are mechanically restrained (e.g., by attaching them to a backup support structure), high stresses result. Tube stresses are lowest when the tubes are not physically joined along their length. The present design allows relative movement between the supply and collection manifolds, which results in significant bending relief and reduction in tube stresses. (The copper bars shown in Fig. 2 were inadvertently added in the fabrication phase but were melted away in early operation.)

The water supply and return lines (4-in. Sch 40 stainless steel pipe) were sized to minimize the pressure drop relative to that through the tube arrays. The correlation presented by Gambill et al. [Eq. (21) of Ref. 3] was used to estimate pressure drops in swirl tubes and found to be very adequate for design purposes.

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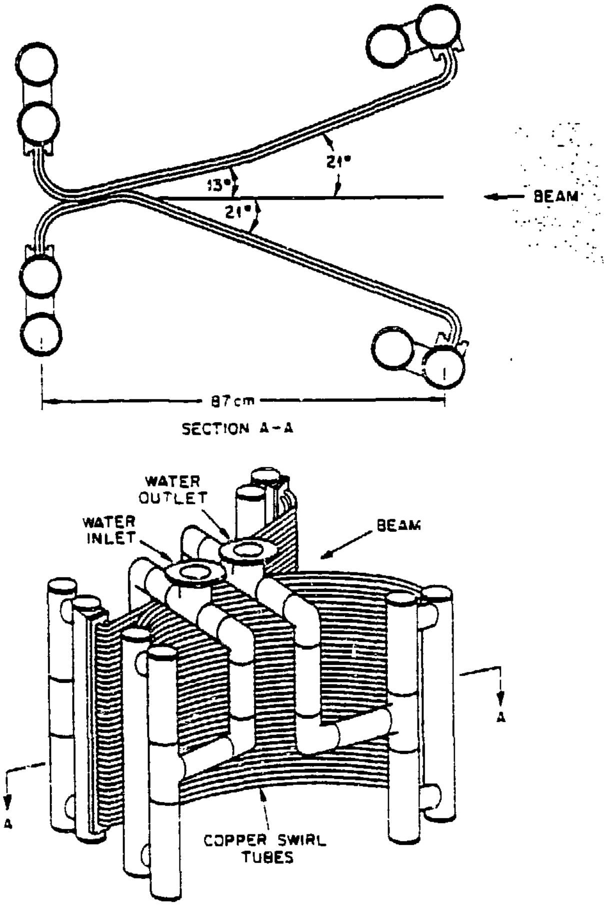

Fig. 1. Schematic of swirl-tube target.

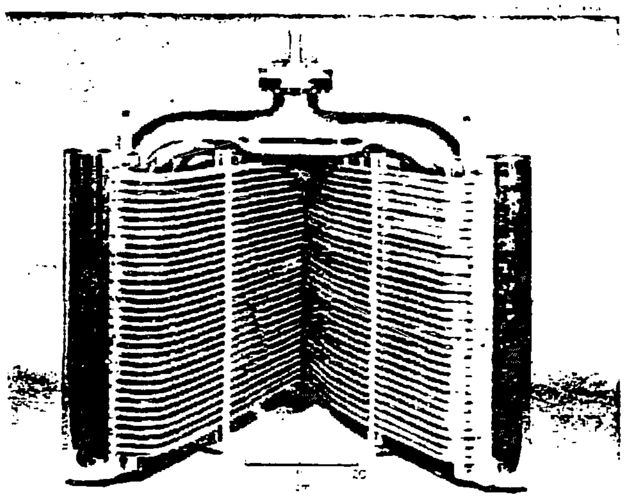

Fig. 2. Photograph of swirl-tube target.

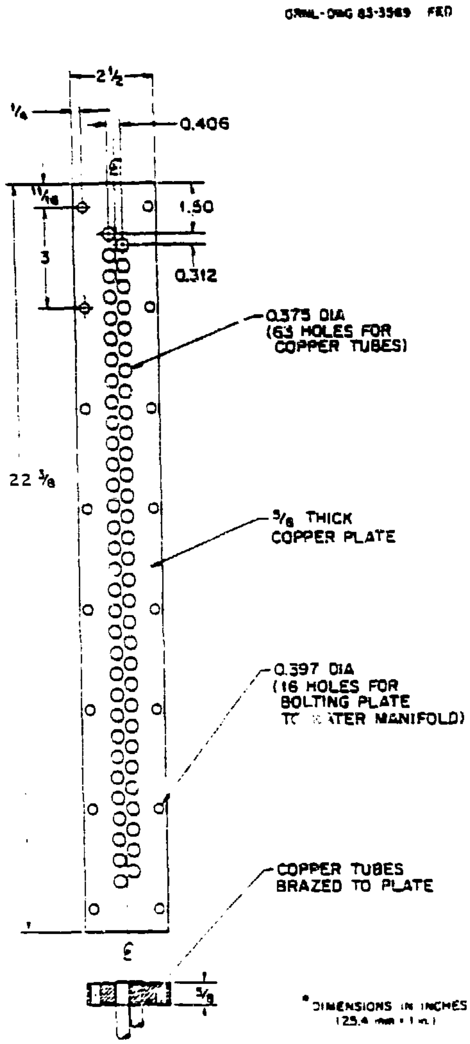

Fig. 3. Drawing of copper plate used for copper tube/water manifold interfaces.

Tube arrays were also constructed using internally finned OFHC copper tubes (supplied by Forge Fin Division of Noranda Metal Industries, Inc.*). These tubes also had a 0.95-cm outside diameter with a 0.076-cm wall thickness, and contained 16 fins, each 0.109 cm high and 0.038 cm thick, about a 5° helix. As mentioned earlier, the target design allows changeout of tube arrays with minimal effort. However, these alternate tube arrays have not yet been tested.

Target Performance

The test location of the target in the ORNL Medium Energy Test Facility is shown in Fig. 4. Maximum test parameters are listed in Table 1. Briefly, the target has handled up to 3-MW, 30-s beam pulses with no deleterious effects. The power source was the ORNL long-pulse ion source; maximum operating parameters to date include 75 kV at 40 A for 30 s. The total water flow rate through the target was 41.6 L/s (660 gpm), which translates to 0.33 L/s (5.2 gpm) per tube or an axial flow velocity of ≈11.6 m/s. The corresponding pressure drop across the target was 1.14 MPa (165 psi) with an inlet water pressure of 1.45 MPa (210 psia). For an extracted power from the ion source of 3 MW and these flow conditions, a temperature difference of 15.7°C was measured across the cooling water, indicating that 2.73 MW was transferred to the target. This represents 91% of the extracted power, and another ≈5% was accounted for in other parts of the neutral beam injection system, so that ≈96% of the total power was accounted for.

The information shown in Fig. 5 can be used to estimate peak power densities on the target during neutral beam operation. The curves were generated using the techniques described by Kim and Whealton[10] for evaluating beam intensity distributions in neutral beam injection systems. The power density is shown as a function of downstream distance for an extraction power of 3 MW; curves are presented for beam divergences θ_s of 0.7° and 0.5° (beam optics in this band). The

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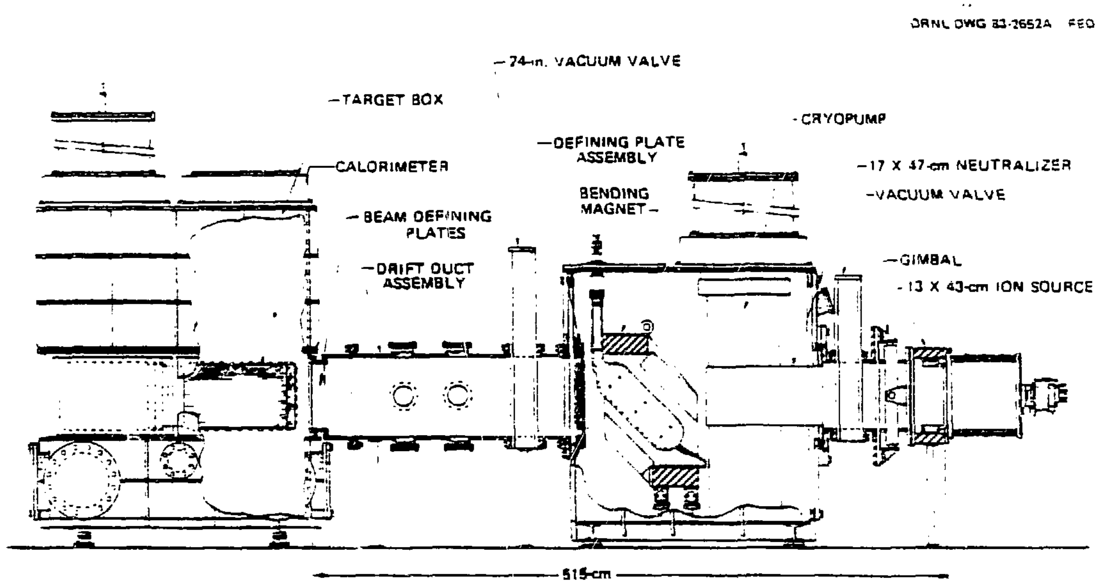

Fig. 4. Schematic of ORNL Medium Energy Test Facility.

Table 1. Maximum test parameters for target

Test location: ORNL Medium Energy Test Facility

Power source: ORNL long-pulse ion source
- Voltage: 75 kV
- Current: 40 A
- Time: 30 s
- Extracted power: 3 MW
- Extraction surface: 13.2 × 43.7 cm
- Focal length: 950 cm
- Power density: ≈15 kW/cm^2 at 640 cm downstream

Target: Inclined water-cooled swirl tubes (126 copper tubes)
- Angle (α) between tube arrays and beam axis: 13° and 21°
- Water flow rate: 41.6 L/s (600 gpm) [0.33 L/s (5.2 gpm) per tube]
- Water velocity: 11.6 m/s
- Inlet water pressure: 1.45 MPa (210 psia)
- Outlet water pressure: 0.31 MPa (45 psia)
- Temperature difference (ΔT): 15.7°C
- Measured power: 2.7 MW
- Tube surface heat flux: ≈5.4 kW/cm^2

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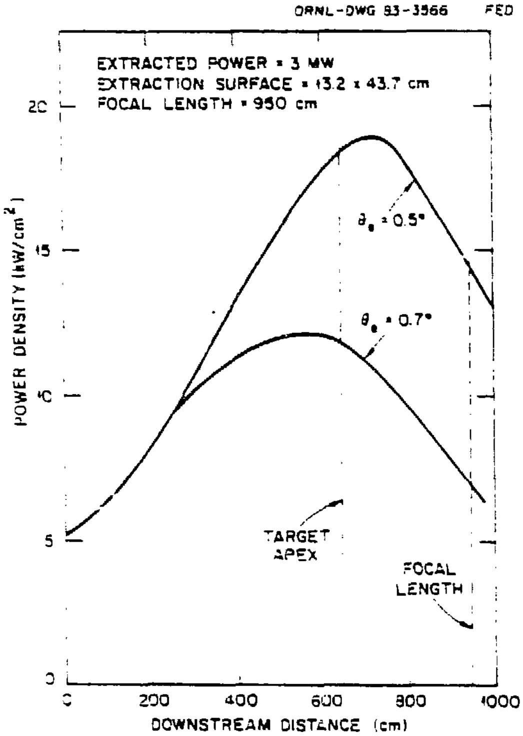

Fig. 5. Calculated peak power density as a function of downstream position for the ORNL long-pulse ion source.

focal length of the beam is 950 cm, and the apex is the target, which was located ≈640 cm downstream of the ion source in these tests. Taking an average value between the two curves in Fig. 5 gives a power density of ≈15 kW/cm^2. This translates to a peak heat flux on the tube surfaces of ≈5.4 kW/cm^2. (The angle α between beam axis and tube array reduces the surface flux by 1/sin α where maximum α = 21°.)

To date the target has intercepted ≈1000 beam pulses lasting from 1 to 30 s and ≈5000 pulses lasting less than 1 s. Color movies taken of the tube arrays during pulsing showed significant movement of individual tubes, especially near the apex (and center) of the target. However, close visual inspection revealed no apparent damage.

Backup Experiments with Individual Tubes

Backup experiments with individual tubes were conducted in a test stand equipped with a 10-cm-diam ion source to characterize tube performance. Most of the information presented in this section was obtained during pulsing of the source at 26 kV and 6 A, for which the peak power density was ≈4.2 kW/cm^2. For power levels above this, the operation of the source was unstable most of the time. The test tubes were positioned in a horizontal orientation normal to the beam. In most tests the water flow rate was ≈0.32 L/s (5 gpm) to duplicate that in the actual target.

The data in Fig. 6 were taken with an infrared camera that scanned along a fixed horizontal line at a rate of 625 μs/scan. For these tests the source was pulsed for 1 s, and the scan was along the horizontal line on the tube surface of maximum temperature. The temperature is related to the instrument output by a simple power law relationship [$T(°C) = 22.3\,(mV)^{0.4}$]. On the time scale (200 ms/div) in Fig. 6(a), the camera scans 320 times per division and essentially tracks peak temperature with time. The surface temperature of the swirl tube reached a peak of 196°C within ≈400 ms [the time constant (τ) was estimated to be ≈80 ms from the data in Fig. 6(a)]. In Fig. 6(b) the camera output indicates the thermal distribution along the tube; two scans are shown for steady-state conditions (770 ms after initiation of pulse). The peak temperature of 196°C in Fig. 6(b) agrees with that in Fig. 6(a).

In Fig. 7 the heat flux distribution measured on the swirl-tube surface is presented. Two techniques were employed in making the measurements: (1) a

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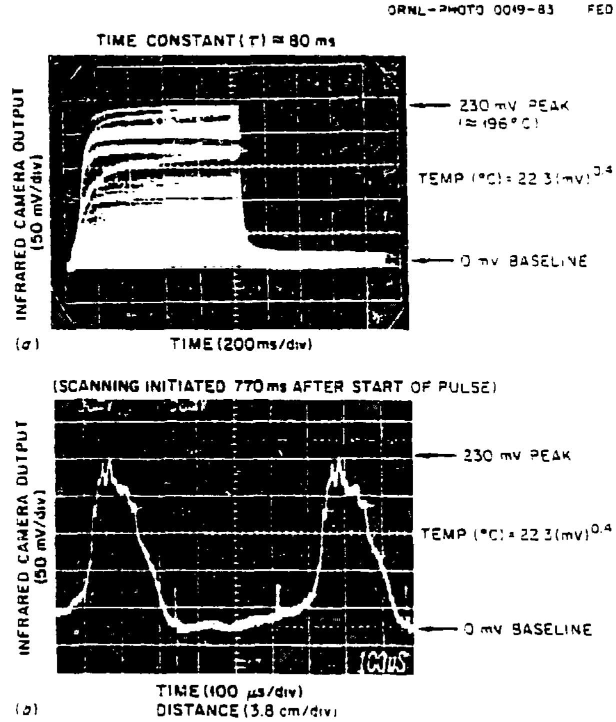

Fig. 6. Thermal data taken with infrared camera scanning swirl-tube surface during pulsing of the 10-cm-diam ion source: (a) peak thermal history and (b) thermal distribution along tube surface (water velocity through tube at ≈11.3 m/s and source operating at 26 kV and 6 A).

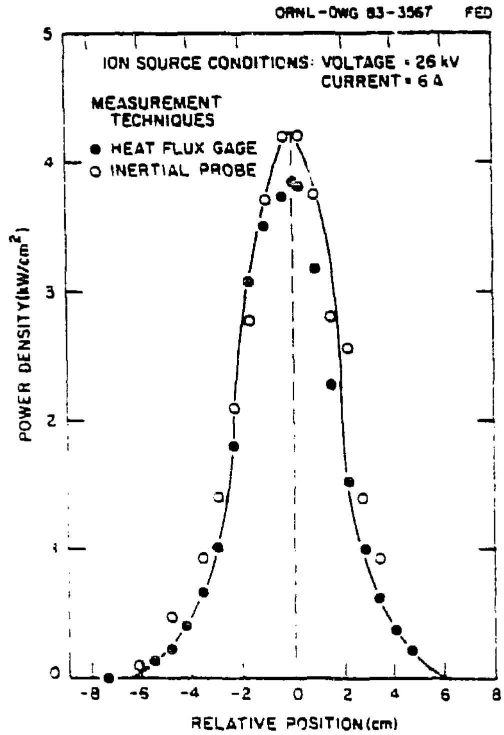

Fig. 7. Measured power density distribution for a neutral beam produced by the 10-cm-diam ion source (measurements made downstream near tube testing site).

circular foil heat-flux gage in which the steady-state heat flux is measured and (2) an inertial-type calorimetry probe in which ΔT is measured and integrated in time to obtain the energy in a beam pulse. The calorimetry probe senses very small temperature differences at the low power densities, resulting in higher uncertainties; likewise, the heat-flux gage is approaching its limit at the higher power densities. Thus, the curve in Fig. 7 is accordingly fitted to the data. The peak power density was found to be ≈4.2 kW/cm² for 26-kV, 6-A operation. For the data in Fig. 7, the ion source was pulsed for 100–200 ms, and measurements were made along a central chord of the beam (corresponding to a profile along the test tube surface).

Some experiments were also performed in which various tubes were tested to burnout. These resulted in punctures through tube walls and thus water leaks, which are incompatible with the high vacuum systems and sophisticated ion sources. Therefore, only a limited number of tests was conducted. Tube samples are pictured and some test conditions listed in Fig. 8. The heated length was determined by the beam size (Fig. 7). All three types of tubes (smooth, swirl, and finned) survived peak heat fluxes of ≈4.2 kW/cm² at the higher water velocities (7.2–11.3 m/s); the swirl tube even survived this condition at a very low water velocity (3.8 m/s). Burnout was observed at ≈4.2 kW/cm² in a smooth tube at a water velocity of 7.8 m/s and in an internally finned tube (as described in the section on target design) at a water velocity of 4.3 m/s. Also, in one test a swirl tube survived a peak power density of ≈7 kW/cm² (26 kV, 6 A, and 500 ms) at a water velocity of 6.7 m/s. This represents only 60% of the present flow in the target tubes. The swirl-tube burnout data suggest that levels of up to 10 kW/cm² or even higher are probably achievable at the present target flow conditions [0.33 L/s (5.2 gpm) per tube or an axial velocity of 11.6 m/s]. This is consistent with the conclusions reached by Thompson et al.[9] and supported by their data. A power

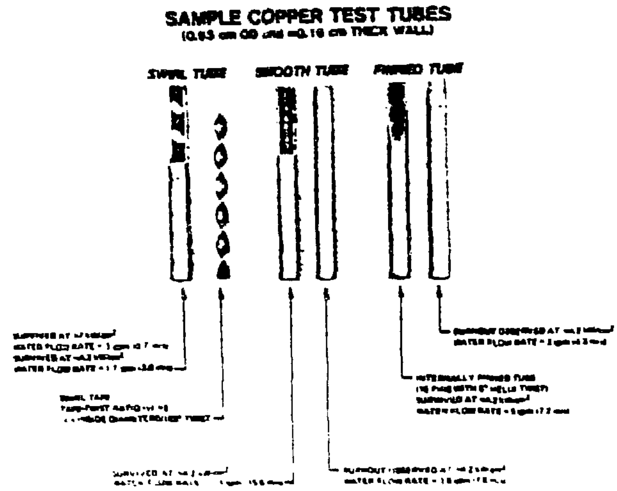

Fig. 8. Photographs of 0.95-cm-OD sample tubes used in burnout experiments (some corresponding test conditions are listed).

density of 10 kW/cm² on the tube surfaces translates to peak power densities in the range from ≈25 to 30 kW/cm² normal to the beam axis. The total beam power associated with these peak power densities is approximately 5 to 6 MW for equivalent beam optics.

Conclusions

The water-cooled, swirl-tube target described in this paper has been qualified at 3 MW for 30 s in tests with the ORNL long-pulse ion source; the plate power density was estimated to be ≈15 kW/cm² normal to the beam axis (≈5.4 kW/cm² maximum on tube surfaces). In these tests, the water flow rate through the target was 41.6 L/s (660 gpm) or 0.33 L/s (5.2 gpm) per tube (axial flow velocity of 11.6 m/s) with a corresponding pressure drop of 1.14 MPa (165 psia). These flow parameters represent the limit of the water supply system now available at the ORNL Medium Energy Test Facility. However, results from burnout tests indicate that the target should handle ≈5–6 MW with this flow. These power levels translate to peak power densities in the range ≈25–30 kW/cm² (≈10 kW/cm² maximum on tube surfaces). Even higher power levels could be achieved with increased flow parameters (i.e., greater water velocities and associated pumping power).

This discussion considers tube burnout as the only failure mode; however, thermal stress levels and the cyclic nature of neutral beam operation are important factors in determining the lifetime of the swirl tubes in the target. Experiments with individual tubes show that tube surfaces essentially reach steady state in ≈400 ms (5τ) of neutral beam pulsing. To date the target has survived ≈1000 pulses lasting 1–30 s and ≈5000 pulses lasting less than 1 s with no apparent damage. The lifetime of the target for these unusually high heat-flux levels has not been estimated. It depends on the power levels and pulse lengths, which have not yet been determined.

The cooling techniques developed here are applicable to other areas involving high heat fluxes. Two such areas in fusion technology are radio-frequency heating components and limiter design.

Acknowledgments

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