TN 62-25
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April 25, 1962

DISCUSSION OF ACCELERATOR COOLING WATER REQUIREMENTS

INTRODUCTION

A series of recent technical notes and memoranda[1] have discussed various aspects of temperature control of the Two-Mile Accelerator. It is the purpose of this note to attempt to clarify some of the questions which have been raised in the reference studies and thereby to proceed further along the path leading to the final design of this important sub-system of the accelerator complex.

REVIEW OF BASIC PRINCIPLES

To obtain maximum electron energy from each accelerator section, it is necessary to maintain its temperature at that value which will cause the section to assume the design dimensions, i.e., the physical size which will result in rf wave propagation at the velocity of light. A temperature deviation δT from the design temperature will cause a phase velocity deviation δv_p given by

$$\frac{\delta v_p}{v_p} = -\left(\frac{v_p}{v_g} - 1\right) g \, \delta T \qquad (1)$$

where g is the linear coefficient of expansion of the accelerator structure material (g for copper = 1.6×10^{-5} per degree C) and v_g is the group velocity in the accelerator structure. This change in phase velocity causes a phase shift $\delta\varphi$ of the rf wave with respect

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[1] G. C. Rogers, "Accelerator Cooling and Temperature Contol", TN 62-20, 3/27/62
A. V. Lisin, "Tentative Water-Jacket Water Requirements", TN 62-23, 4/9/62
F. Hall, "Status of Cooling Water Studies", memorandum to R. B. Neal, 4/11/62
G. C. Rogers, "Cooling Water Studies", memorandum to R. B. Neal, 4/18/62
C. H. Sphar, "Cooling Water System", memorandum to R. B. Neal, 4/19/62
A. V. Lisin, "Cooling the Accelerator and Waveguide by a Series Flow Arrangement", TN 62-21, 4/62
J. Jurow, "Accelerator Cooling and Temperature Control (II)", memorandum to F. Hall, 4/19/62

to the electron bunches (assuming electron velocity = c) which is given by:

$$\delta\varphi = -2\pi \frac{\delta v_p}{v_p} \frac{z}{\lambda_o} \quad \text{(radians)} \tag{2}$$

where z is the distance along the accelerator axis and λ_o is the free space wavelength.

The fractional beam-energy loss in the constant impedance accelerator structure caused by the above phase shift is given by[1]:

$$\frac{\delta V}{V_o} = -\frac{1}{6} (\delta\varphi)^2 \left[\frac{6}{\tau^2} - \frac{3\tau + 6}{\tau(e^\tau - 1)} \right] \tag{3}$$

where τ is the attenuation constant of the accelerator structure in nepers.

Inserting the appropriate values for the M Accelerator in Eqs. (1), (2), (3), we obtain the results

$$\delta\varphi = -0.234 \ \delta T \quad \text{(radians)} \tag{4}$$

$$\frac{\delta V}{V_o} = -8.1 \times 10^{-3} (\delta T)^2 \tag{5}$$

where δT is the temperature error in degrees C. For example, to obtain $\frac{\delta V}{V_o} < .005$, the temperature deviation δT must not exceed $\pm\ 0.8°C$ ($\pm\ 1.4°F$) and the resulting phase shift in this case would be 10.7 degrees.

EFFECTS OF TEMPERATURE DEVIATIONS

Temperature deviations have two effects on the output beam characteristics:

(1) They cause a reduction in beam energy as indicated in Eq. (5);

(2) They may result in a broadening of the energy spectrum.

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[1]Neal, M.L. Report 185, pp. 55-57, February 1953. [The fractional energy loss in the constant gradient structure is somewhat less than that given in Eq. (3) - see Neal, Report No. M-169, May 1960.]

The second effect does not occur if the temperature deviations of the accelerator sections have a random distribution such that the algebraic sum of the phase shifts in all the sections is zero. In this case, the electrons are ahead of the wave crest as much on the average as they are behind the crest during their transit through the accelerator and the percentage spectrum width remains unchanged.

DISCUSSION OF SECTOR CONTROL

In the case of sector control of cooling water temperature, the temperature deviations of individual sections are the sum of three separate components:

(1) The error in the determination of the "correct" temperature at which the sector should be maintained;

(2) The error in the temperature of the water to the entire sector;

(3) The error in the temperature of the metal structures of individual sections.

The "correct" base temperature for the sector cooling water depends upon the average power level. In this discussion, it is presumed that the klystrons in the sector are all operated at the same nominal beam voltage, pulse length, and pulse repetition rate. It is desired to maintain the accelerator sections at a constant temperature at all power levels. To accomplish this, the input cooling water temperature must be lower than the temperature of the metal structure of the accelerator section by an amount proportional to the average rf power input to the section. Among the several ways by which the correct input water temperature may be determined are the following: (a) by monitoring the temperature of the metal of the accelerator structure using appropriate sensing devices and maintaining the mean metal temperature constant[1] by adjusting the input cooling water temperature (for improved accuracy, the average temperature of all the sections comprising the sector should be maintained constant; the average might be determined, for example,

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[1]It is important to take into account the temperature drop across the metal wall of the accelerator structure. For copper walls and for the parameters of the M Accelerator this temperature drop is given by $\delta T = 0.053\ t\ P_{KW}$, where t is the wall thickness in inches and P_{KW} is the average rf power input in kilowatts to the accelerator section. At the maximum Stage II power level of 21.6 kw and for $t = 3/8$ inch, $\delta T = 0.43^{\circ}C$. The pertinent temperature drop governing cavity dimensions is approximately $\delta T/2$ which has a maximum Stage II value of $0.22^{\circ}C(0.39^{\circ}F)$.

by connecting all the sensing devices attached to the individual accelerator sections of the sector in series) (b) by monitoring the average output power of the dc supply connected to the sector modulators and by multiplying this output by the known klystron efficiency factor; (c) by measuring the water temperatures in the supply and return manifolds of the accelerator sector and by maintaining the input water temperature at a value determined from this difference; (d) by monitoring the rf phase difference between the input and output of the "control" accelerator section and by adjusting the input water temperature to keep this phase difference constant. Of the four methods outlined here, method (d) should be most accurate and has the advantage that the temperature drop across the accelerator wall is automatically taken care of; however, it would probably be more expensive to instrument than the others. Method (a) would probably give sufficient accuracy with reasonable cost. The accuracy of methods (b) and (c) is affected by beam loading variations but they might still be adequate.

The magnitude or errors in class (2) depend upon the accuracy to which temperatures can be maintained in economically feasible control systems. Rogers in TN 62-20 states that a control system has been developed which can easily maintain water temperatures within $\pm 0.2^{\circ}F$. For the purpose of this note, it will be assumed that the sum of errors in classes (1) and (2) can be held to $\pm 0.4^{\circ}F$, except during transient periods.

Errors in class (3) arise primarily from variations in the average output power of individual klystrons. Since the difference in the temperature of the metal accelerator structure and the input cooling water temperature is proportional to the average rf power input, a deviation of input power from the standard value on which the input water temperature is based will result in a deviation in the temperature of the metal wall from the correct value. At the maximum Stage II power level, approximately 15 kw of rf power is dissipated in each accelerator section (in the absence of beam loading).

Lisin[1] has calculated and experimentally verified the temperature difference between the input cooling water and the metal accelerator structure at various values of power dissipation and water flow rates

[1] A. V. Lisin, "Tentative Water Jacket Requirements", TN 62-23, Supplement No. 1, 4/19/62.

for a 10-foot accelerator structure equipped with 16 - 0.43 inch inside diameter pipes carrying cooling water in a counter-flow arrangement. He finds, for example, that for a power dissipation of 15 kw and a flow rate of 20 gallons/minute the temperature difference is 10.4°F. At a given flow rate, the temperature difference is proportional to power dissipation. However, for a given power dissipation, the temperature difference does not increase proportionally when the flow rate is decreased (e.g., at 15 kw dissipation and 10 gal/min flow the difference is 16.2°F). From the above results it is clear that, at a flow rate of 20 gal/min, variations of ± 10% in the output of individual klystrons (due to manufacturing tolerances, aging, variation in rf drive, etc.) from the nominal value would (at maximum Stage II power level) cause ± 1°F variations in the temperature of the accelerator sections receiving the power from the affected klystrons. The corresponding temperature variations in the case of 10 gal/min flow rate would be ± 1.6°F, etc.

CONCLUSIONS

If the output of all klystrons in the sector fall within a 20% band and if the correct sector water temperature can be determined and maintained within ± 0.4°F, then, for a cooling water flow rate of 20 gal/min to each accelerator section, the reduction in electron energy gain from temperature effects in the case of sector control of cooling water temperature will not be greater than 0.5% for the maximum Stage II power input. For a flow rate of 10 gal/min and with other assumptions the same as above, the electron energy reduction from temperature effects will not be greater than 1.0%. At lower values of average power input the percentage reduction in energy will be even less.

If the variation in klystron power outputs are randomly distributed with respect to the "norm" used as the basis for sector water temperature determination, the energy spectrum width will not be increased by the spread in rf power outputs.

If the temperature accuracy assumptions made in this note can be realized in an economically feasible control system it would appear that sector control of cooling water temperature is practicable under both Stage I and Stage II conditions and that it should be adopted.