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TITLE: TEMPERATURE RISE AND GRADIENT OF SLC POSITRON
 ACCELERATING SECTION AND WAY TO REDUCE
 THEIR EFFECTS ON POSITRON DYNAMICS

What are the temperature rise and gradient on high accelerating gradient section following the positron target and their effects on positron dynamics is a problem concerned about at present time.

Temperature equations are approximately as follows:

$$\begin{aligned} q(z,t) - A\alpha[T_a(z,t) - T_w(z,t)] &= M_a C_a \frac{\delta T_a(z,t)}{\delta t} \\ A\alpha[T_a(z,t) - T_w(z,t)] - FC_w \frac{\delta T_w(z,t)}{\delta z} &= M_w C_w \frac{\delta T_w(z,t)}{\delta t} \end{aligned} \quad (1)$$

Where T_w is water flow temperature distribution. T_a structure temperature distribution. C_a and C_w are specific heat of copper and water, respectively. M_a and M_w are mass of structure and water per unit length, respectively. F water flow rate. A is contact area between cooling water and metal wall per unit length. $q(z,t)$ is heat source. α is heat transfer coefficient between copper and water which comes from experiments.

The equations can be solved by making Laplace transform with respect to time t or distance z .

At first, the time constant of temperature rise of structure can be roughly found from the solution to the equations at $z = 0$ (inlet of cooling water). Then setting $\delta T_a / \delta t = u$ and $\delta T_w / \delta t = 0$, we can find temperature distribution along the structure at stable state and average temperature rise of the structure as well as temperature gradient along the structure.

Two kinds of structure are considered: Constant Gradient one (C.G.) and Constant Impedance one (C.I.).

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Three kinds of water flow arrangement are considered: Normal (*N*) and Reverse (*R*) as well as *U* form (*U*). At *U* form water first flow from the end of the structure to the head and then turn back, so the inlets and outlets of water tubes are all located at the end of the structure. At *N* form water flow from head to end of structure and at *R* form it is inverse.

Some Formulas from Solving Equation (1)

T_i - Time constant of temperature rise.

$T_a(z)$ - Temperature distribution along the structure.

dT - Maximum Temperature difference on the structure.

aT - Average Temperature rise of the structure.

(a) C.I. Structure

$$\text{Heat source : } q(z, t) = 2 \cdot I \cdot P_0 \cdot \text{Exp}(-2IZ) \cdot H(t) \quad (2)$$

N Case:

$$T_i = M_a C_a / A \alpha \quad (3.1)$$

$$T_a(z) = \frac{P_0}{FC_w} + P_0 \cdot \text{Exp}(-2IZ) \cdot \left(\frac{2I}{A \alpha} - \frac{1}{FC_w} \right) \quad (3.2)$$

$$dT = P_0 \left(\frac{2I}{A \alpha} - \frac{1}{FC_w} \right) (1 - \text{Exp}(-2IL)) \quad (3.3)$$

$$aT = \frac{P_0}{FC_w} + P_0 \left(\frac{2I}{A \alpha} - \frac{1}{FC_w} \right) \frac{1 - \text{Exp}(-2IL)}{2IL} \quad (3.4)$$

R Case:

$$T_i = M_a C_a / A \alpha \quad (4.1)$$

$$T_a(z) = P_0 \left(\frac{1}{FC_w} + \frac{2I}{A \alpha} \right) \times \text{Exp}(-2IZ) - \frac{P_0}{FC_w} \cdot \text{Exp}(-2IL) \quad (4.2)$$

$$dT = P_0 \left(\frac{1}{FC_w} + \frac{2I}{A \alpha} \right) \cdot (1 - \text{Exp}(-2IL)) \quad (4.3)$$

$$aT = P_0 \left(\frac{1}{FC_w} + \frac{2I}{A\alpha} \right) \frac{1 - \text{Exp}(-2IL)}{2IL} - \frac{P_0}{FC_w} \cdot \text{Exp}(-2IL) \quad (4.4)$$

U Case:

$$T_i = M_a C_a / A\alpha \quad (5.1)$$

$$T_a(z) = \frac{2IP_0}{A\alpha} \cdot \text{Exp}(-2IZ) + \frac{P_0}{2FC_w} (1 - \text{Exp}(-2IL)) \quad (5.2)$$

$$dT = \frac{2IP_0}{A\alpha} (1 - \text{Exp}(-2IL)) \quad (5.3)$$

$$aT = P_0 \left(\frac{1}{A\alpha L} + \frac{1}{2FC_w} \right) \cdot (1 - \text{Exp}(-2IL)) \quad (5.4)$$

(b) C.G. Structure

$$\text{Heat source: } q(z,t) = 2I_0 P_0 \times H(t) = Q \times H(t), \quad Q = 2I_0 P_0 = \text{Constant} \quad (6)$$

N or R Case:

$$T_i = M_a C_a / A\alpha \quad (7.1)$$

$$T_a(z) = Q \left(\frac{1}{A\alpha} + \frac{z}{FC_w} \right) \quad (7.2)$$

Temperature moves up along direction of water flow.

$$dT = QL / FC_w \quad (7.3)$$

$$aT = Q \left(\frac{L}{2FC_w} + \frac{1}{A\alpha} \right) \quad (7.4)$$

U Case:

$$T_i = M_a C_a / A\alpha \quad (8.1)$$

$$T_a(z) = Q \left(\frac{1}{A\alpha} + \frac{L}{2FC_w} \right) = \text{Constant} \quad (8.2)$$

$$dT = 0 \quad (8.3)$$

Some approximate characteristics follow:

- (a) U Form is good for C.G. Structure because of $dT = 0$.
- (b) dT is independent of water flow rate F at U Form for C.I. Structure.
- (c) $dT = 0$ when $F = A\alpha/2IC_W$ at N Form for C.I. Structure.

An example: MIT Linac with high duty cycle has long sections of 7.4 m with approximately C.G. performance. Heat deposition per cavity is about 140 W. Water flow arrangement is R Form. Water flow rate $F = 100 \text{ GPM}$. The number of tubes is 8 with I.D. = 16 mm. The measurements indicate that temperature is higher at the head of the structure than at the end and the difference between them is about 1.25°C as well as the average temperature rise is about 2.5°C . The numbers computed by formulas (7.3) and (7.4) are $dT = 1.12^\circ\text{C}$ and 2.9°C respectively. In calculations the A is considered to equal tube number $\times$ its circumference of inside wall, i.e., $A = 8 \times 3.1416 \times 0.016 \text{ m} = 0.402 \text{ m}$.

The Results of Calculation

In our case the structure is constant impedance one and has U Form water tube arrangement. There are 24 tubes on outside wall of the structure and inside diameter of tube is 0.25 inch. Some other parameters are listed below:

$$\begin{aligned}
 F &= 27.4 \text{ GPM} \times 3.7853/60 = 1.73 \text{ Kg/Sec}; & V_g &= 0.0134 \text{ C}; \\
 \alpha &= 1000 \text{ Cal}/(^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{Sec}); & f_0 &= 2856 \text{ MHz}; \\
 A &= 24 \times 3.1416 \times 0.25 \text{ inch} = 0.479 \text{ m}; & C_a &= 90 \text{ Cal}/(^{\circ}\text{C} \cdot \text{Kg}); \\
 M_a &= 41 \text{ Kg}; & L &= 1.5 \text{ m}.
 \end{aligned}$$

Heat source consists of positron shower disposition and RF loss. It's distribution is shown in Fig. 1 with mark * and is fitted with formula (2) by adjusting the parameters I and P_0 . The fitted curve is also shown in Fig. 1 with $I = 0.6 \text{ 1/m}$ and $P_0 = 20.5 \text{ KW}$ (curve 1). Curve 2 shows the temperature distribution along the structure computed by formula (5.2). The average temperature rise $\Delta T = 6.9^\circ\text{C}$ by formula (5.4) and maximum temperature difference $dT = 10.2^\circ\text{C}$ by formula (5.3) as well as time constant of temperature rise is about 7.7 sec. by formula (5.1).

For comparison we list more results computed with different F and A in Table 1.

TABLE 1

A (m)	F (GPM)	U FORM		N FORM		R FORM	
		$dT(^{\circ}C)$	$aT(^{\circ}C)$	$dT(^{\circ}C)$	$aT(^{\circ}C)$	$dT(^{\circ}C)$	$aT(^{\circ}C)$
0.479	27.4	10.2	6.9	7.9	7.2	12.6	6.5
	54.8	10.2	6.3	9.1	6.5	11.4	6.1
	100.	10.2	6.0	9.6	6.1	10.9	5.9
0.6	27.4	8.2	5.7	5.8	6.1	10.5	5.4
	54.8	8.2	5.1	7.0	5.3	9.4	5.0
	100.	8.2	4.9	7.5	5.0	8.8	4.8
only RF	27.4	1.2	2.8	0.3	2.8	2.2	2.7
loss	54.8	1.2	2.5	0.7	2.6	1.7	2.5
0.479	100.	1.2	2.4	1.0	2.4	1.5	2.4

Note: $A = 0.6$ m corresponds to I.D. of tube = 7.95 mm.

It can be seen from Table 1 that N Form water tube arrangement and properly largening I.D. of tube may be better.

The Way to Reduce Effects of Temperature Gradient on Positron Dynamics

Temperature change in an accelerating structure causes the shift of the resonant frequency and the phase velocity of the travelling wave. In our case (U FORM)

$$\delta T_a(z) = \frac{2IP_0}{A\alpha} \text{Exp}(-2IZ) + \frac{P_0}{2FCW}(1 - \text{Exp}(-2IL)) \quad (9)$$

$$\delta f_0(z) = k \cdot \delta T_a(z); \quad k = -50 \text{ kHz}/^{\circ}C \quad (10)$$

and phase velocity change are

$$\frac{\delta V_p}{V_p} = - \left(1 - \frac{c}{V_g}\right) \cdot \frac{\delta f_0}{f_0} \quad (11)$$

The integrated phase shift at z caused by the temperature change is

$$d\phi(z) = \int_0^z \frac{2\pi}{\lambda} \delta \left(\frac{c}{V_p} - 1 \right) dz = -\frac{2\pi c}{\lambda V_p} \int_0^z \frac{\delta V_p}{V_p} dz = \frac{2\pi}{\lambda f} \left(1 - \frac{c}{V_g}\right) \int_0^z \delta f(z) dz \quad (12)$$

If a temperature sensor is set up at m^{th} cavity and the temperature of m^{th} cavity is kept correct by adjusting input cooling water temperature, the formulas of temperature change and integrated phase shift along the structure are as follows respectively (in U FORM):

$$\delta T_a(z) = \frac{dT}{1 - \text{Exp}(-2IL)} (\text{Exp}(-2IZ) - \text{Exp}(-2ImD)) \quad (13)$$

$$\delta \phi(z) = \frac{2\pi}{\lambda} \left(1 - \frac{c}{V_g}\right) \frac{k}{f} \frac{dT}{1 - \text{Exp}(-2IL)} \left[\frac{1 - \text{Exp}(-2IZ)}{2I} - z \cdot \text{Exp}(-2ImD) \right] + \phi_0 \quad (14)$$

Where dT is temperature difference between the head and the end of the structure. ϕ_0 is initial phase of positron with respect to wave. Some results computed are shown in Fig. 2. The curve 1 and 2 correspond to cases with $m = 0$, $\phi_0 = 0^\circ$ and $m = 21$, $\phi_0 = -5^\circ$ respectively. It is obviously seen that when $m = 21$ and $\phi_0 = -5^\circ$ the maximum phase deviation of positron from wave crest will be less than 5° . In our case main problems taken care of are not energy loss and spectrum broadening of positron bunch in this one section, and is the change in phase of bunch caught to accelerating state in following sections, so this phase deviation in this section would be acceptable.

Preliminary Conclusions

(a) To adopt the technique mentioned above that has been successfully used in MIT and SACLAY medium energy Linac with high duty cycle can greatly reduce the effects of temperature rise and gradient caused by positron shower and RF loss on positron dynamics. A group of temperature sensors are set up along the structure. The best position for sensor is near 2/3 length of the structure of C.G. one. In our case (C.I. one) it maybe is near the middle of one. Besides, we can get a number of useful data about temperature distribution on positron accelerating section.

(b) To adopt N FORM water arrangement is simpler structurally and, perhaps, is more effective in improvement of temperature rise and gradient (see Fig. 1, curve 3).

(c) To keep good contact (good welding quality and as large contact area as possible) between cooling water tubes and copper wall of the structure is very important.

(d) To properly largen diameter of cooling water tube (for example I.D. varies from 6.35 mm to 7.95 mm) is advantageous (see Fig. 1, curve 4).

(e) To pay special attention to cooling head plate of structure because of high heat disposition caused by positron shower.

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46 0700

Fig. 1. Temperature distribution of structure

fig. 1

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