Fermilab Linac Upgrade Side Coupled Cavity Temperature Control System*

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ABSTRACT

Each cavity section has a temperature control system which maintains the resonant frequency by exploiting the 17.8 ppm/°C frequency sensitivity of the copper cavities. Each accelerating cell has a cooling tube brazed azimuthally to the outside surface. Alternate supply and return connection to the water manifolds reduce temperature gradients and maintain physical alignment of the cavity string. Special tubing with spiral inner fins and a large flow rate are used to reduce the film coefficient. Temperature is controlled by mixing chilled water with the water circulating between the cavity and the cooling skid located outside the radiation enclosure. Chilled water flow is regulated with a valve controlled by a local micro computer. The temperature loop set point will be obtained from a slower loop which corrects the phase error between the cavity section and the rf drive during normal beam loaded conditions. Time constants associated with thermal gradients induced in the cavity with the rf power require programing it to the nominal 7.1 MW level over a 1 minute interval to limit the reverse power.

INTRODUCTION

The linac upgrade project at Fermilab will replace the last 4 drift-tube linac tanks with seven side coupled cavity strings [1]. This will increase the beam energy from 200 to 400 MeV at injection into the Booster accelerator.

The main objective of the temperature loop is to control the resonant frequency of the cavity. A cavity string will consist of 4 sections connected with bridge couplers driven with a 12 MW klystron. Each section is a side coupled cavity chain consisting of 16 accelerating cells and 15 side coupling cells. For the linac upgrade, 7 full cavity strings will be used. Presently a separate temperature control system is planned for each of the 28 accelerating sections, the two transition sections, and the debuncher section.

The cavity strings will be tuned to resonance for full power beam loaded conditions. A separate frequency loop is planned that will sample the phase difference between a monitor placed in the end cell of each section and the rf drive. The frequency loop controls the set point for the temperature loop which maintains the resonant frequency through periods without beam or rf power. The frequency loop will need the intelligence required to determine under what conditions the phase error information is valid and the temperature set point should be changed.

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REQUIREMENTS

The side coupled cavities will be driven at 4 times the frequency of the current linac, or about 805 MHz, and have an unloaded Q of 20,000. For a cavity constructed of a single metal, the percentage change in resonant wavelength will equal the percentage change in linear dimension which is proportional to temperature. A full cavity section had a measured temperature dependance of -14.3 KHz/°C, or 17.8 ppm/°C of 805 MHz.

If the cavity resonant frequency deviates from the drive frequency, power will be reflected from the cavity, causing standing waves within the waveguide. The klystron design specification requires it to withstand a voltage standing wave ratio, or vswr, of up to 1.5:1 at the 12 MW power level. The limit is the breakdown voltage at the ceramic window at the output of the klystron. A temperature error of about .6 °C would generate a vswr of 1.5:1. In comparison, 50 mA of beam loading will generate a vswr of 1.3:1 or require a .2 °C temperature increase with beam. The low level system should be able to maintain the .5% amplitude and .5° phase regulation required through small changes in cavity temperature.

When rf power is applied to the cavity, 200 watts per cell flows through the copper into the cooling water. The thermal resistance of the copper path results in a temperature gradient within the cell. An analysis of the transient heat flow using ANSYS was performed by Jim Olson and Terry Anderson. At 200 watts/cell, a 3.8 °C temperature gradient develops between the nose cones in the accelerating cells and the outside wall with a 1/e time constant of 34 seconds. A full cavity section was measured to have a frequency deviation of -35 KHz for 200 watts/cell of rf excitation.

The resonant frequency shift induced by the rf power could be corrected with a temperature change of -2.4 °C. It would require 62 KW of cooling to maintain the resonant frequency if the rf were abruptly switched on. If the cavity strings are kept at the temperature which provides the correct resonant frequency with nominal power, then the resonant frequency will be 35 KHz too low with no rf power

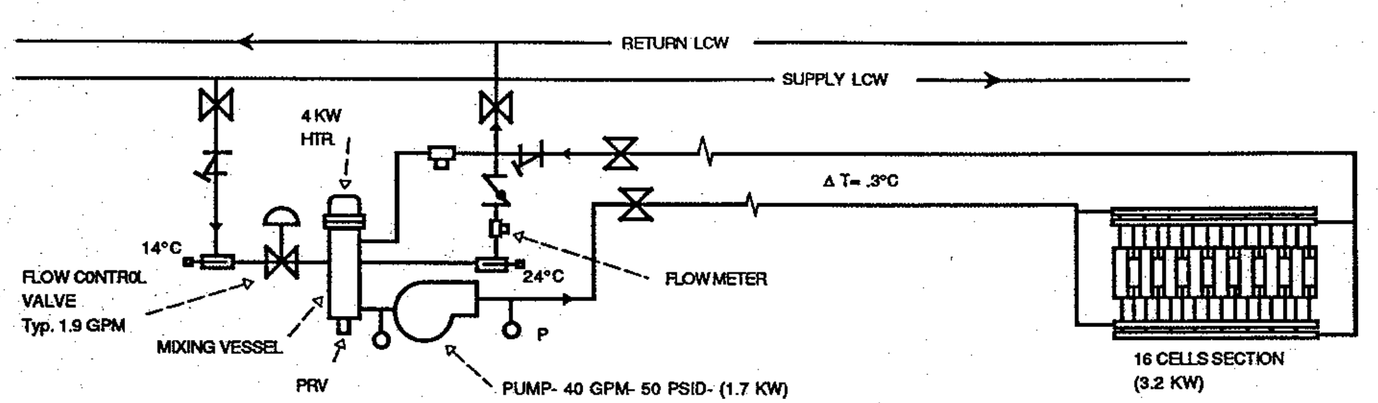

Figure 1. Schematic of typical one section cavity temperature control system.

applied. This will result in a vswr of 4.9:1, or a 3.7 MW power limit. Tom Owens used ACSL to obtain a turn on program which limits the maximum waveguide voltage to that obtained with 12 MW and a vswr of 1.5:1 while gradually increasing the power level. The cavity could reach the correct resonant frequency in about 55 seconds. This process could be automated with the local computer by monitoring the reverse power while increasing the klystron output during turn on, similar to the existing linac.

IMPLEMENTATION

Placing the cooling skids outside of the radiation enclosure has a significant impact on the design of the temperature regulation system. Figure 1 shows a typical one section cavity temperature control system. A pump circulates about 40 gpm of low conducting water, or LCW, between the cooling skid and the cavity. The temperature of the cavity will be maintained by controlling the amount of chilled water mixed with the circulating water. The cooling skids will be up to 95 feet from the cavities. The 36 gallons of water required to fill the system have a heat capacity of 574 KJ/°C compared to the 298 KJ/°C for the 1700 pounds of copper in one section. At 40 gpm, this amount of water requires 54 seconds to make one loop through the system. This delay will limit the closed loop bandwidth and complicate the use of feedforward.

The nominal rf power dissipated in the copper of the cavity will be about 3.2 KW. The water pump will contribute another 1.7 KW. With a chilled water temperature 10 °C below the cavity temperature, 1.9 gpm of chilled water will be required to extract the 4.9 KW of power. At the nominal operating power, the temperature rise across the cavity will be about .3 °C. The cavity operating temperature was chosen to be near room temperature to avoid thermally insulating the cavity.

Water has about 10 times the heat capacity and 650 times the thermal resistance of copper. The large heat capacity makes water an efficient way to transfer heat to the cavities. The thermal resistance makes it difficult to transfer heat between the water and the copper. If the water flow through the cooling tubes on the cavity is slow, little mixing will occur and a large temperature gradient will develop between the flowing water and the tube wall. Special copper tubing with spiral inner fins was used on the cavity with a turbulent flow rate selected to avoid excessive wear. From available literature, the tubing used is expected to have a film coefficient 1.5 times better than a smooth copper tube providing a thermal conductance of about 270 watts/°C per water path for a 2.4 gpm flow rate [2,3]. The time constant formed with the film coefficient of the 17 water paths and the thermal mass of the cavity is about 65 seconds.

CONTROL THEORY

A simple model, applicable to the cavity cooling system, is shown in figure 2. It consists of a container, with water flowing through it, that retains a constant volume. If we assume that the inlet water instantaneously and completely mixes in the volume, then the thermal mass C will be at the outlet temperature Tout. The change in outlet temperature will be equal to the integral of the net power flowing into the volume divided by its thermal capacitance. Assume at time $t = 0$ the system is in steady state, the temperature of thermal mass C is Tout = Tin, and that Tin and the chilled water flow,F , remain fixed.

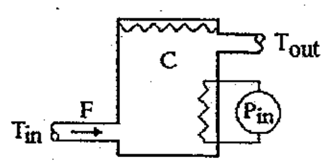

Figure 2. Simple model of cavity temperature control system.

Using Laplace transforms Tout can be found as a function of input power, Pin. Letting A = 3.814 °C-gpm/KW, the heat carrying capacity of water, and ω_0 = F/AC the relationship is provided in equation 1 below.

$$\frac{\overline{T}_{out}}{\overline{P}_{in}} = \frac{A}{F}\frac{\omega_o}{s+\omega_o} \quad \text{equation 1}$$

For small changes in flow and temperature, Tout can be approximated with equation 2 [4].

$$\frac{\overline{T}_{out}}{\overline{F}} = \frac{\Delta T}{F}\frac{\omega_o}{s+\omega_o} \quad \text{equation 2}$$

An integral type of controller was selected for the temperature loop because of the simplicity and the zero steady state error. Figure 3 provides a simple block diagram.

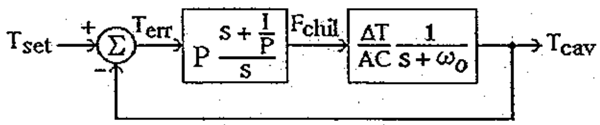

Figure 3. Simple block diagram of cavity temperature control loop.

If I/P is chosen to equal $\omega_o = F/AC$, then the open loop response becomes a simple integrator. The unity gain frequency of the open loop will be the closed loop corner frequency, or closed loop bandwidth $\omega_{cl} = P\,\Delta T/AC$. The closed loop bandwidth will be essentially constant provided the cavity temperature changes are small.

Theoretically the above system could have infinite closed loop bandwidth. Stability requires the open loop gain to be less than one when the phase shift is 180°. A conservative design would have 45° of phase margin, or only 135° of phase shift. The open loop phase shift for the case above is 90° for all frequencies. For the cavity loops, there will be additional phase shift caused by the thermal resistance of the film coefficient and the time required for the water to travel from the cooling skid to the cavity. As shown below, the closed loop bandwidth is limited to about .001 Hz.

for ω_{cl} = .001 Hz	90.0°	controller integrator
	23.4°	film coefficient, (τ = 65 sec)
	9.7°	water travel time, (27 sec)
	5.0°	cavity wall to probe, (τ = 14 sec)
	2.6°	control valve, (τ = 7.3 sec)
	0.6°	thermocouple amp, (τ = 1.6 sec)
	0.4°	computer sample time, (1 sec)
	131.7°	Total phase shift

To improve the accuracy of the chilled water control valve, a separate loop was implemented which maintains measured chilled water flow by controlling the valve. Figure 4 provides an overall block diagram. The loop improved the feedforward accuracy which greatly reduced the time required to recover from a step change in power.

Because of the thermal gradients induced in the cavity, the desired temperature at the probe changes with rf power level. The nominal temperature is chosen to be that which maintains a constant energy stored in the thermal mass of the system. This requires no heating or cooling beyond the steady state levels for changes in power. The temperature must be chosen for the correct resonant frequency at the nominal power level.

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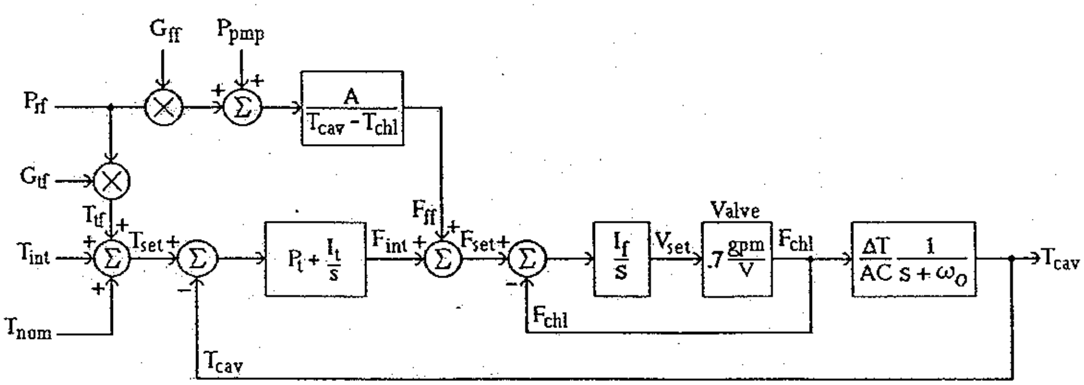

Figure 4. Block diagram of Temperature control loop.

TEMPERATURE (or FREQUENCY) CONTROL SYSTEM

Jim Crisp and John Satti

For a cavity constructed of a single metal, the percentage change in resonant wavelength equals the percentage change in linear dimension, which is proportional to temperature.

Temperature Sensitivity	-14.3 KHz/^{o}C	17.8 ppm/^{o}C of 805 MHz

The total radiation exposer inside the cavity enclosure is expected to be 10^8 rads over the 20 year lifetime of the linac upgrade. To eliminate the effects of radiation damage, the water system is located outside of the enclosure and 200 GPM of LCW, (or low conducting water), is circulated through 200 feet of pipe between the cooling skid and the cavity. The cavity copper temperature is controlled by allowing a measured amount of CLCW, (or chilled LCW), to replace an equal amount of circulating LCW at the cooling skid.

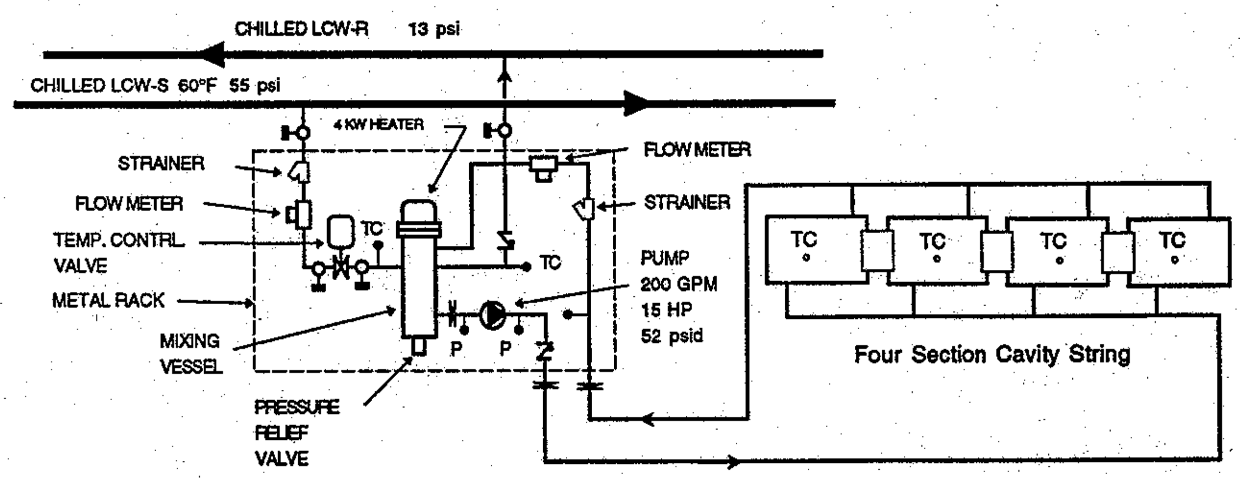

Figure 1. Schematic of cavity string cooling skid.

Under normal conditions there will be a peak rf power of 7.5 MW dissipated in the cavity copper. With a 60 usec pulse width and 15 Hz repetition rate the average rf power is 6.75 KW. In comparison, the pump required to circulate the 200 GPM between the cavity and cooling skid will dissipate 7.5 KW in the water. The cavities are expected to run near room temperature to render radiation and convection losses negligible

Power	rf power	6.75 KW	
	pump power	7.5	
	total	14.25 KW	
Thermal mass	155 Gallons of H_2O	2.44 MJ/^{o}C	90GAL 1.42
	6800 lbs Cu	1.20	
	1360 lbs Fe	.28	
	total	3.92 MJ/^{o}C	2.90 MJ/°C

open loop 1/e time constant 2751 seconds 45.9 minutes

The Temperature control loop was implemented inside the local station computer. Since the parameters required to control the cavity temperature should be monitored through the computer already, only software is required to implement the loops. Because the computer also monitors rf power and waveguide to cavity phase, implementing feedforward and the separate phase loop was simplified over a stand alone controller.

The control loop is a simple integral controller selected for its zero steady state error. The closed loop bandwidth is limited to .001 Hz by the 88 second time constant formed by the film coefficient and the 48 second water travel time. The 1/e closed loop time constant of 160 seconds is about 17 times faster than the open loop.

closed loop 1/e time constant 160 seconds

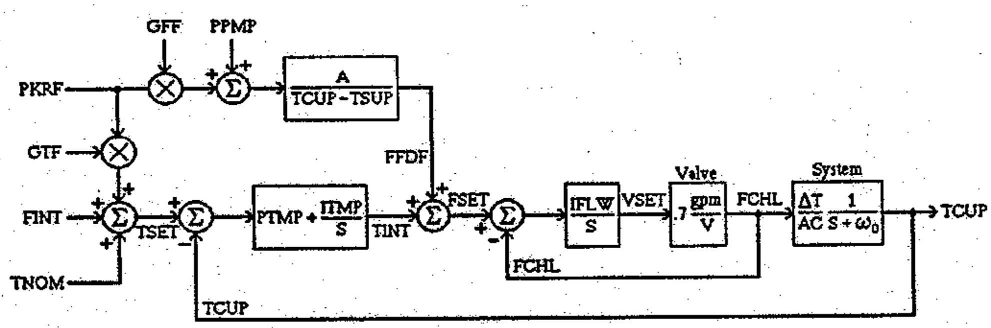

Figure 2. Block diagram of temperature control loop.

Large closed loop bandwidth, or open loop gain, is desirable to reduce the effects of unpredictable changes in the system. Predictable changes can be reduced with feedforward. Accurate control of the CLCW flow was obtained by inclosing the control valve in a separate loop using a precision flow turbine. Measured rf power, cavity, and CLCW temperatures are used to program the flow directly. Over a 4 day period the cavity temperature was observed to change by less than .07 ^{o}C and the resonant frequency by 600 Hz, (.8ppm of 805 MHz).

Water is a good thermal insulator. At the inside surface of the cooling tubes attached to the cavity, water moves slowly which allows a thermal barrier to form. Higher flow rates induce turbulence which reduces the thermal gradient but increases erosion of the cooling tubes. The 1/2 inch copper tubing used on the cavities is internally finned to improve the film coefficient. The resulting thermal resistance is 240 Watts/^{o}C at 2.9 GPM per cooling path, 50% better than smooth copper tube. The 68 cooling paths and the 6.75 KW of rf power conspire to induce a .41 ^{o}C temperature gradient between the cavity surface and the cooling water. The total flow rate of 200 GPM provides a .13 ^{o}C temperature difference between supply and return. The 34

PSI pressure drop across the cavity contributes an additional .06 ^{o}C to this difference. To minimize the temperature gradients, supply and return are reversed on neighboring cooling tubes.

The nominal rf power produces a 1.84 ^{o}C temperature gradient between the cavity nose cones and the cooling tube. The corresponding frequency change is -14.9 KHz and the 1/e time constant is 43 seconds for a step change in power. The 39 KJ/^{o}C thermal mass of the nose cones represents only 1% of the total system thermal mass. To keep the frequency constant during turn on, 95 KW of cooling, or heating for turn off, would be required to control the temperature of the remaining 99%. A more cost effective solution is to maintain the bulk of the thermal mass at that temperature which provides the desired resonant frequency for nominal power and program the frequency during turn on. Presently the frequency program is calculated by the computer from the cavity temperature and a running average of the rf power. When the calculated frequency is within 2 KHz of the nominal frequency, the program snaps to the nominal value and the phase loop is enabled. The slower phase loop adjusts the cavity operating temperature to minimize the waveguide to cavity phase error.

Recent tests demonstrate that for a step change in power of 1 to 7.5 MW peak, only 50 seconds were required to reach within 2 KHz of the nominal operating frequency. The maximum waveguide to cavity phase error of 3^{o} (2.2 KHz), is well within the 25^{o} range of the low level rf system.

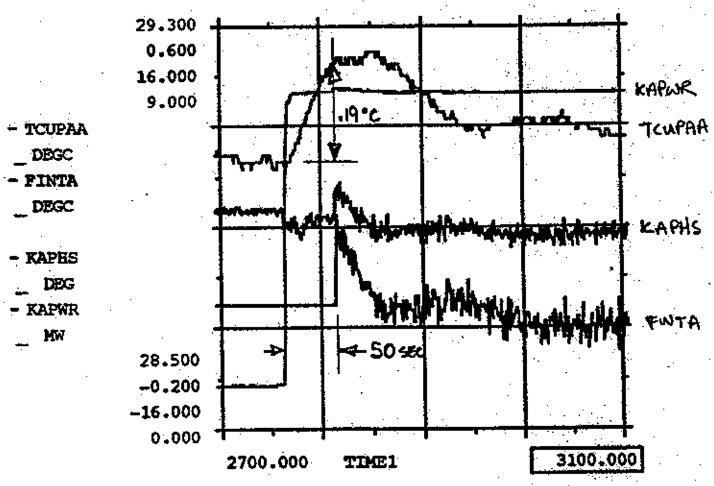

Figure 3. Step response for a 1 MW to 7.5 MW power change.

With 50 mAmps of beam current and 32^{o} accelerating angle, the cavity resonant frequency should be 2.8 KHz below the drive frequency to keep the total cavity current in phase with the voltage. This will require running the cavities .2 ^{o}C warmer.

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