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IMPROVING THE PHASE STABILITY OF THE SLAC RF DRIVELINE NETWORK FOR SLC OPERATION*

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Summary

Successful operation of the Stanford Linear Collider (SLC) will require greater phase stability from the two-mile long RF drive network than previous linac operation did. This paper discusses four proposed modifications of the present system that should help achieve the general objective to reduce all long term temperature and atmospheric pressure induced phase variations to less than 20° at 2856 MHz, so that the phase/amplitude detector subsystems, which will control the network output phases relative to a beam reference, will operate within their most accurate ranges.

Introduction

Some upgrading of the present linac RF driveline network should greatly increase the network's long-term phase stability. This paper discusses specifically four proposed modifications: 1) main drive line (MDL) gas pressure (dielectric constant) control, 2) subdrive line (SDL) thermal isolation and gas pressure regulation, 3) SLED cavities temperature control via bypass water flow control and feed-forward control on the supply water temperature, and 4) drive line and beam-derived phase comparisons periodically made along the linac. These modifications are directed at reducing the effective temperature and pressure variables, so that there will not be large (> 20°ϕ at 2856 MHz), long-term variations in the MDL, SDL and SLED cavities phase lengths as a result of daily and seasonal atmospheric changes and programmed changes of the accelerator duty cycle.

A phase reference line (PRL) is to be paralleled along each SDL, and amplitude and phase detectors[1] at the outputs of the SLED cavities will allow precise phase adjustments to be made to the network to compensate for amplifier-induced phase shifts and various not-fully-compensated phase drifts. It should be noted that the individual PRL's are only as stable as their drives from the MDL and thus modification four, which would provide a direct comparison with the beam, is essential for checking long-term stability. The other modifications would allow the subsystem discussed in Ref. 1 to perform more accurately and over a smaller dynamic range.

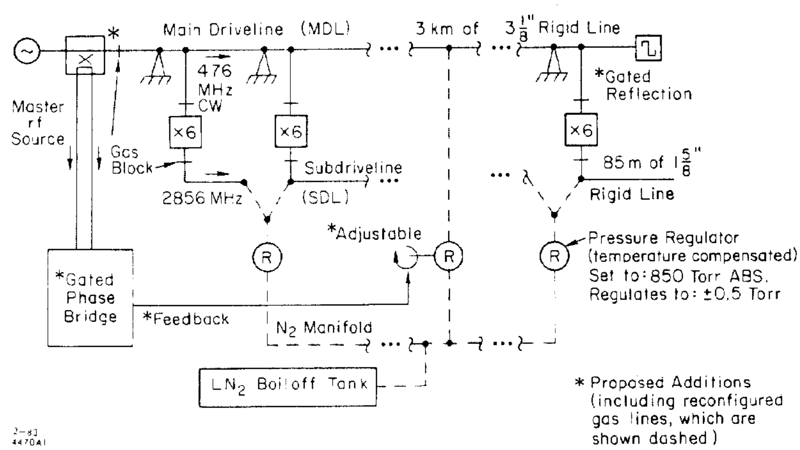

Fig. 1. RF driveline phase length stabilization, fixed nitrogen pressure regulation of the subdrive lines and adjustable pressure regulation of the main drive line with feedback from a phase length measurement of the whole MDL.

1. MDL Gas Pressure Control

The main drive line operates at 476 MHz, the one-sixth subharmonic of the 2856 MHz linac RF frequency. It is mechanically constrained and fitted with expansion joints at each of the 30 signal coupling points along its 3 km length. Thus, the expansion of the concrete floors (both in the above-ground RF gallery, to which the MDL is anchored, and in the underground accelerator tunnel to which the accelerator is attached) and changes in the coaxial line's dielectric constant are the primary causes of phase length variations. The change in phase length of the 3 km-long line relative to the beam is given approximately by:

$$d\theta_T = \frac{\partial\theta}{\partial\varepsilon}\left[\frac{\partial\varepsilon}{T_\varepsilon}\, dT_\varepsilon + \frac{\partial\varepsilon}{\partial p_\varepsilon}\, dp_\varepsilon\right] + \frac{\partial\theta}{\partial\ell}\cdot\frac{\partial\ell}{\partial T_a}\, dT_a \qquad (1)$$

or

$$d\theta_T(^\circ\phi) = -25 dT_\varepsilon(^\circ C) + 3.4 dp_\varepsilon(\mathrm{Torr}) + \theta_a' dT_a(^\circ C) \quad , \qquad (2)$$

where θ_T is the total equivalent phase length at 2856 MHz in degrees of electrical phase, ε is the relative dielectric constant (teflon supports plus nitrogen gas), T_ε is the temperature of the dielectric, T_a is the outdoor air temperature, θ_a' is the effective differential expansion coefficient of the two pieces of concrete to which the accelerator downstairs and the MDL upstairs are anchored, and p_ε is the N_2 gas pressure inside the coaxial line. It should be noted that if the MDL were not anchored at the signal coupling points the last term in Eq. (1) would be considerably larger since the expansion of copper, and not the upstairs concrete slab, would be involved. Since θ_T is what is really of interest and independent measurements of the concrete expansions are difficult, a measurement of the whole MDL, as shown in Fig. 1 is suggested. Also, assuming that the $\theta_a' dT_a$ term in Eq. (2) is comparable to or less than the other two terms, it is clear that the total phase length can be kept constant if the gas pressure is varied to compensate for temperature changes. This is valid as far as diurnal and seasonal temperature changes are concerned, and they are the primary causes of long-term phase shifts. It is proposed that the MDL phase length measurements be made continuously, periodically or on command, depending upon need and in a manner similar to that used on PEP.[2] One adjustable pressure regulator at the center of the MDL, controlled by the gated phase bridge, should be optimum provided that the leak rate of the line is kept low. Otherwise, ganged regulators may be necessary. This scheme does not compensate for nonuniform phase shifts along the MDL. However, due to the uniform layout of the RF gallery, these should be only small ripples on the general phase drift. If necessary, local variations could be detected with the technique discussed in Section 4, below.

2. SDL Thermal Isolation and Gas Pressure Regulation

The subdrive line can be treated differently from the main drive line since the much shorter length reduces the dielectric effects, the lack of anchors between couplers increases the thermal expansion effect, and finally installation of a parallel PRL with phase detectors allows correction of any phase shifts. The equation corresponding to Eq. (1) for the 85 m long SDL is:

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$$d\theta_T = \frac{\partial\theta}{\partial\varepsilon}\left[\frac{\partial\varepsilon}{\partial T_\varepsilon}\, dT_\varepsilon + \frac{\partial\varepsilon}{\partial p_\varepsilon}\, dp_\varepsilon\right] + \frac{\partial\theta}{\partial\ell}\cdot\frac{\partial\ell}{\partial T}\, dT_{cu} \qquad (3)$$

$$d\theta_T(^\circ C) = -0.71 dT_\varepsilon(^\circ C) + 0.09 dp\ (\mathrm{Torr}) + 4.88 dT_{cu}(^\circ C) \qquad (4)$$

Since $T_\varepsilon \doteq T_{cu}$ (the copper line temperature),

$$d\theta_T \doteq +4.2 dT_\varepsilon(^\circ C) + 0.09 dp_\varepsilon(\mathrm{Torr})\ . \qquad (5)$$

From Eq. (5) it is clear that p_ε has a small effect on the SDL length; therefore, it can be regulated to a fixed value as shown in Fig. 1. If the dynamic range of the PRL phase detectors is desired to be kept small or they are not used in a particular case, a thermal isolation jacket may have to be installed on the SDL. The "thermal Faraday cage" enclosing the 1 5/8 line in Fig. 2 has been shown to decrease the temperature drop between the water and the coaxial line by a factor of forty or more over the water-to-air temperature drop. The epoxied tube configuration shown on the MDL in Fig. 2 produces a factor of about four to ten only. This is acceptable for the MDL since it is anchored and since pressure adjustments on the MDL for temperature-induced dielectric constant changes are a reasonable alternative to greater temperature isolation.

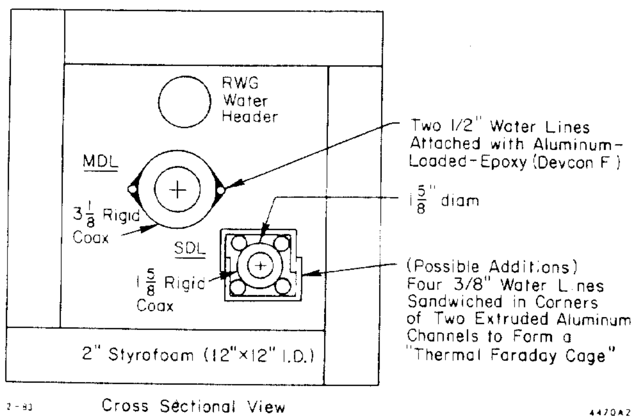

Fig. 2. Thermal enclosures for the main drive line and the subdrive lines.

3. SLED Cavities Temperature Control

The phase shift through the SLED cavities and the accelerator sections is a strong function of the average power dissipated in them because of significant temperature gradients in their cooling circuits. Furthermore, the RF pulse width affects the percentage of the klystron power that is lost in the SLED cavities on the way to the accelerator sections. For the present operation of SLED with a 2.5 μs pulse, only 8% of the total power is absorbed by the SLED cavities. With the 5 μs pulse required for SLC, 24% is absorbed. Currently, all the accelerator water first passes through the SLED cavities. This large flow of water for a 2.5 μs wide pulse keeps them at nearly fixed temperature and phase shift; i.e., on resonance. Since the accelerator section's input water temperature is supposedly optimized for midway between the two duty cycles normally used (60 pps or 180 pps at 2.5 μs) they work reasonably well at either repetition rate. Since SLC requires greater stability than is currently needed, some way of tracking the SLED and accelerator temperatures with duty cycle changes is highly desirable. A careful examination of the SLED cavity and accelerator section thermal equivalent circuits reveals that the SLED cavities are "over cooled" and bypassing an appropriate fraction $(1-\beta)$ of the total accelerator section water would allow the phase shift across both the SLED cavities and the accelerator sections to remain constant, if simultaneously the supply water temperature were changed a predetermined amount. This required supply temperature offset is dependent only on the total average power out of the klystron. If heat loss to the air is neglected, β is dependent only on the pulse width, the water flow rate and the fixed geometry of the cooling circuits and not the klystron power. Since the input water temperature is adjusted on a sector-wide basis, if one klystron out of the eight in a sector is lower or higher in output power, that has to be compensated for by adjusting the total flow to its SLED cavities and accelerator sections, in order to keep the metal temperatures constant. This will have a small effect on β and can easily be accomplished by adjusting the four valves shown in Fig. 3 at the inputs to the accelerator sections.

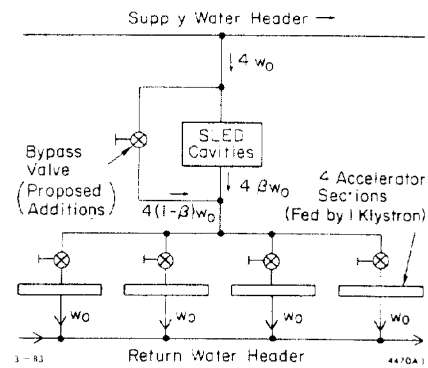

Fig. 3. Balancing the SLED cavities and accelerator sections water circuits.

Simplified forms of the equations for the average metal temperatures of the SLED and accelerator sections, $\bar{T}_{ms}$ and $\bar{T}_{mg}$, respectively, in terms of the input water temperature, T_{in}, the water flow, w_0, through a single accelerator section and the average power, $\bar{P}_0$, out of a klystron and excluding losses to the air are given by:

$$\bar{T}_{ms} \doteq T_{in} + 3.41\left[\frac{R_{mks}}{4} + \frac{R'_{mhs} + \frac{1}{2}}{4 w_0 \beta}\right](1-\eta_s)\,\bar{P}_0\ , \qquad (6)$$

$$\bar{T}_{mg} \doteq T_{in} + 3.41\left\{\frac{1-\eta_s}{4 w_0} + \left[R_{mkg} + \frac{1}{w_0}\left(R'_{mhg} + \frac{1}{2}\right)\right]\eta_s\eta_R(1-\eta_g)\right\}\bar{P}_0\ , \qquad (7)$$

R_{mks} and R_{mkg} are average resistivities due to the thermal conductivity paths in the SLED and accelerator sections, respectively. The R'_{mhs} and R'_{mhg} are the respective metal-water film drop resistivities with the inverse water flow dependence multiplied out. The fractional power out of the SLED cavities is η_s, that out of each of the four branches of the waveguide feeds to the four accelerator sections is η_R, and that out of an accelerator section is η_g, each relative to its input power.

If T_{in} is programmed as a function of $\bar{P}_0$ (duty cycle) to keep $\bar{T}_{ms} = \bar{T}_{mg} = 45^\circ C$, β can be found in terms of various constants and operating parameters, and then the phase lengths of the SLED cavities and accelerator sections will remain constant. As in Eqs. (6) and (7), if the heat loss to the air is neglected, β is independent of P_0 or,

$$\beta = \frac{(R'_{mhs} + \frac{1}{2})}{1 - w_0 R_{mks} + 4(w_0 R_{mkg} + R'_{mhg} + \frac{1}{2})\left[\eta_s\eta_R(1-\eta_g)/(1-\eta_s)\right]}\ . \qquad (8)$$

For typical values of the constants,

$$\beta = \frac{(1-\eta_s)}{1.1\eta_s - 0.15}\ . \qquad (9)$$

A 2.5 μs pulse means $\eta_s = 0.92$ and gives a β of 0.09. Both 4 μs and 5 μs pulse widths are under consideration for SLC operation, which would mean $\eta_s = 0.82$ and 0.76 and that would give $\beta = 0.24$ and 0.35, respectively.

Thus, a bypass that could be set to cover a β from 0.08 to 0.40 should allow pulse width variations from 2.5 μs to 5.0 μs without any mechanical retuning of the SLED cavities. Also, the small amount of SLED cavity mistuning still resulting from duty cycle changes should not move the SLED cavities far enough off resonance to lose appreciable power and the phase-detection-feedback subsystem[1] should be able to compensate for the less than $10^{\circ}\varphi$ phase shifts incurred in the process.

4. Beam Phase References for the RF Drive Line Network

The above proposals deal with modifications to the drive line network so as to make individual parts more stable. This section deals with measuring that stability at the input to the phase reference lines (PRL) relative to the beam phase, as shown in Fig. 4.

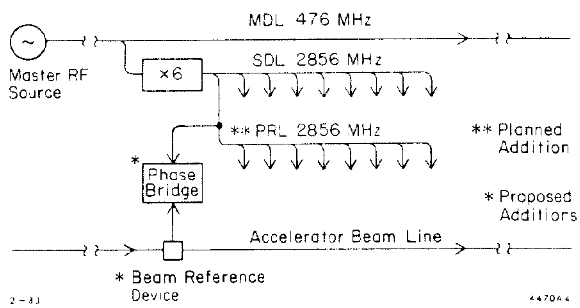

Fig. 4. Beam "phase" reference for the phase reference lines, typical of thirty circuits (sectors) along the linac.

The difficulty lies in getting a "phase-bridge-useable" signal from three single SLC beam pulses that are separated by 58 ns and occur at a rate of 180 pps. Currently, the following beam reference devices are the primary candidates:[3] a) a single resonant cavity tuned to the linac RF frequency, b) a short accelerating structure that is not driven, c) a standard 3 m long accelerating structure with the driving RF delayed infrequently in order to make the measurement and d) a laser amplitude modulated at 2856 MHz and sent through the evacuated alignment pipe with couplers and demodulators every sector. Another candidate[4] involves comparing the PRL's end-to-beginning along the full 3 km in the RF gallery, but it has cumulative error problems. Also, neither this scheme nor the laser directly involves the beam as a reference. However, it would be useful for detecting and locating 6X frequency multiplier problems and MDL nonuniformities by comparing one PRL line with another. The laser scheme would be the nicest since it can be on whether the beam is on or not, but a reliable modulator and demodulator at 2856 MHz seems to be a research project in itself.

A single resonant cavity already exists at the end of each sector as part of the microwave beam position monitor circuitry. In order to achieve a nominal $\pm 1^{\circ}\varphi$, reference stability, the cavity must be tuned such that its resonant frequency is close enough to the linac frequency so that the phase of the cavity does not "walk" away before the phase comparison with the PRL can be made. For example, if the phase uncertainty of the measurement, $\Delta\theta$, is to be less than $\pm 1^{\circ}\varphi$, the cavity resonant frequency drift, Δf, must be less than ± 50 kHz and the measurement interval after ringing starts, Δt, must be less than 55 ns, since $\Delta\theta \leq 360\ \Delta f\,\Delta t$. This is reasonable and implies a copper cavity temperature stability of $\pm 1.0^{\circ}$C. If the Q_L of the cavity is at least 1000, the ringing or decay time will be at least 117 ns, which also should be fine for the above measurement. The final requirement is that the cable between the PRL and the resonant cavity should not vary in phase either. Temperature control and measurement of its length[5] periodically as part of the monitoring circuitry should satisfy that requirement.

If a series of coupled cavities, such as some length of an accelerator section, is used then the output signal would be constant in amplitude. Also, the phase shift during the pulse would be a measure of the correct tuning (temperature) of the structure and thus the device could be easily calibrated. For example, a twenty cavity, 70 cm long structure, installed at the end of each sector, would have a phase-temperature sensitivity of $1^{\circ}\phi/^{\circ}$C and would put out a 180 ns long pulse for the passage of a single beam bunch. The alternative is to use one of the standard 3 m accelerating sections with the klystron RF switched momentarily to standby for the beam phase measurement. Of course, some sort of limiter and/or diode switch would have to be incorporated in the gated phase bridge to protect it from the klystron's output. Also, both a special short section and a standard section would have the same requirements on the cable to the phase bridge as the above mentioned single resonant cavity. More work is needed to determine which of the devices would be optimum.

In conclusion, there is much that can be done on the RF drive line network to optimize the overall reliability and stability and to complement the installation of the PRL and phase detector subsystem discussed in reference one.

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