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RF PHASE DISTRIBUTION SYSTEMS AT THE SLC*

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ABSTRACT

Modern large linear accelerators require RF distribution systems with minimal phase drifts and errors. Through the use of existing RF coaxial waveguides, and additional installation of phase reference cables and monitoring equipment, stable RF distribution for the SLC has been achieved. This paper discusses the design and performance of SLAC systems, and some design considerations for future colliders.

INTRODUCTION

The SLAC 3 km linac[1] consists of approximately 960 3.05-m-long disk-loaded accelerating sections, powered by approximately 240 high-power klystron stations. The linac is further divided into 31 discrete sectors of klystrons, where each sector has a low-power subbooster klystron, which provides RF drive for approximately eight high-power accelerator klystrons.

RF distribution systems to any accelerator must meet and exceed the intrinsic phase stability specification required of the high-power RF devices powering the accelerator. Large accelerators are especially vulnerable to any environmentally driven or induced changes.

The SLAC accelerator has a variety of RF distribution systems, applied to meet the various needs of the accelerator. We describe herein the systems, and present various operational and design considerations.

RF DISTRIBUTION SYSTEMS

The RF source for all accelerator components is the Main Drive Line (MDL). This line runs along the ceiling of the accelerator, and at each of 31 sectors, provides RF at the subharmonic frequency of 476 MHz for klystron and timing instrumentation. At each sector, a timing fiducial is extracted from the RF, and the frequency is multiplied by 6 to 2856 MHz. This signal is distributed the 100 m length of the sector on a special Phase Reference Line (PRL), and is supplied to the subbooster klystron for generation of the pulsed drive for the accelerator klystrons. The pulsed drive signal is distributed the length of the sector in its own subdrive line to each klystron. Each subbooster and klystron station is instrumented with a phase detector which measures the difference between the phase of the reference line and the RF entering the accelerator.

The Main Drive Line

The MDL is a rigid, gas-filled coaxial wave-guide which runs the length of the accelerator. It provides the primary RF drive and phase reference for all subboosters and klystrons, and is the largest single source of slow drifts. The phase stability of the accelerator is dependent on this line, and any drifts or changes in the phase of the line affect the phase stability of all RF devices.

The MDL is mounted on rollers near the ceiling of the klystron gallery, equipped with periodic expansion joints, and rigidly attached to the concrete floor near the beginning of each sector, thus rendering each sector's RF phase insensitive to the "linear" temperature variation dependence

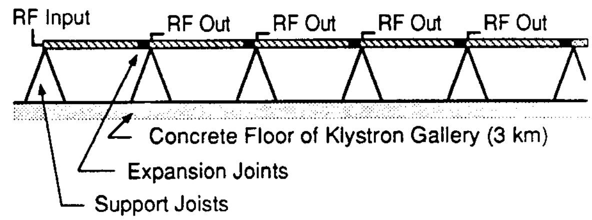

Fig. 1: The MDL runs the accelerator length in the klystron gallery. RF is distributed to the local RF distribution system in each sector, where timing information is extracted, and frequency is increased by a factor of 6. Attachment to gallery floor helps decrease temperature dependance by constraining the physical line length.

commonly associated with thermal metal expansion. Figure 1 shows the support arrangement.

A phase drift of 10° (at 3 GHz) over a 12-hour period (corresponding to an electrical length change of a ppm) is a serious concern for SLC linac operations; uncompensated phase drifts of 100° (10 ppm) would be catastrophic. Drifts of 40° are regularly observed.

When the line length is fixed, the RF systems are only sensitive to changes in the "dielectric delay" of the cable. The dielectric delay is the difference in the line velocity, and the electron beam velocity, or the light speed. For this type of line, the nominal velocity of propagation is around 0.9975 *c*, differing from the beam speed by only 0.25%.[2] The RF stability specification of 10° corresponds to a stability in the dielectric delay of 400 ppm. Stabilities in this region are not achieved, but with the use of an interferometer as part of an active feedback system, stability can be achieved.

Length changes in the MDL are attributed to changes in the dielectric properties of the Nitrogen gas and the internal Teflon support structure of the rigid coaxial line. Gas changes are driven by molar density changes due to both temperature and pressure changes, while the Teflon is sensitive to temperature variations.

The gas dielectric is Nitrogen, which is continuously purged into the line. Gas loss is entirely due to leaks in the MDL, the expansion joints, and the sector subdrive lines. The line operates at a negligible over-pressure, and the internal pressure is strongly driven by the area's barometric pressure changes. Fortunately, this part of California seldom sees large pressure fronts. Continuous purging of the MDL also keeps atmospheric water vapor from entering the line; water vapor is very damaging to the stability of RF cables, largely because the polar moment of water vapor results in a significant dielectric constant change in the gas at microwave frequencies, and the changes occur only near the leaks, not uniformly distributed along the length of the line.

The Teflon spacers support the central conductor, and are part of each joint and expansion joint. The integrated length of the Teflon spacers in the 3 km line is around 18 m, and is a significant source of the line's dielectric delay. Unfortunately, predicting the temperature dependencies of this component is very difficult.

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To compensate for any changes in the dielectric delays, the line is equipped with an electrical interferometer.[3] The interferometer monitors any changes in the round-trip phase length of the MDL. Modulated reflections are generated on the downstream end of the MDL, and a synchronous detector at the source end detects any phase length differences. Changes in the monitored length are presumed to be uniformly distributed along the length of the line, and phase shifts are applied to the subbooster drive klystron in each sector to remove any phase errors.[4]

Figure 2 shows a week of data from the MDL interferometer, gas pressure inside the line, and metal temperature of the line at a representative point. The detected length can be derived from the temperature and pressure terms, and is:

$$\phi_{MDL} = -83.1 + -2.64\cdot(P_{MDL}-1013) + 1.36\cdot(T_{MDL}-95).$$

This is in agreement with the theoretical expectations. The residual on the fit is less than 2° (@ 3 GHz). The offset term (-83.1) is instrumentational, and is sensitive to any hardware modifications in the master source or the interferometer system.

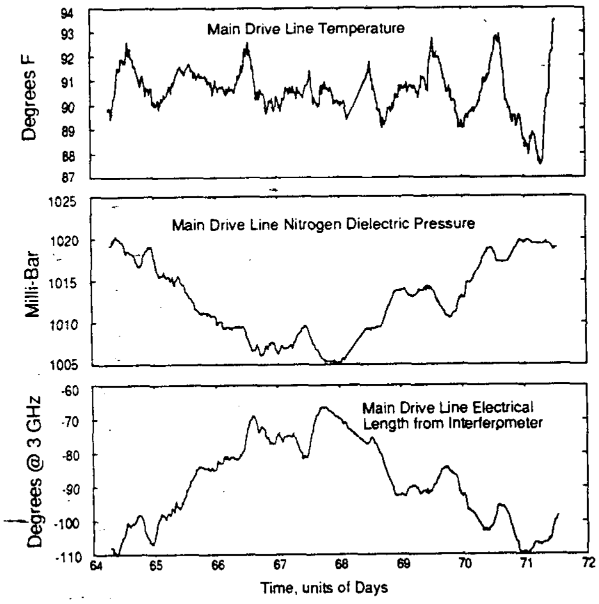

Fig. 2: Shown is the interferometry data on the SLAC MDL. This 3-km-long coax is subject to length changes as the N_2 gas dielectric and Teflon supports change temperature and pressure. Also shown is the temperature and pressure history for the same period.

The Phase Reference Line

Within each linac sector is a 100 m PRL, providing the reference to phase detectors at each RF station. This line consists of several lengths of 1/2-inch foam dielectric, phase-stabilized, Andrews[5] Heliax coaxial cable. Each length is insulated, and hung from the ceiling; RF couplers are installed between lengths.

Two watts of RF is supplied to each line from the RF distribution and frequency multiplier at the head of each sector. Taps from the cable are used as the local phase reference for phase and amplitude detectors[6] at the high-power klystron stations. The line terminates at a phase detector at the beginning of the next sector, allowing diagnostics of both the RF distribution and multipliers, and the phase reference line itself.

Figure 3 shows a one-week history of the results of two adjacent sets of sectors' phase detectors. Note the diurnal variations driven by ambient temperatures.

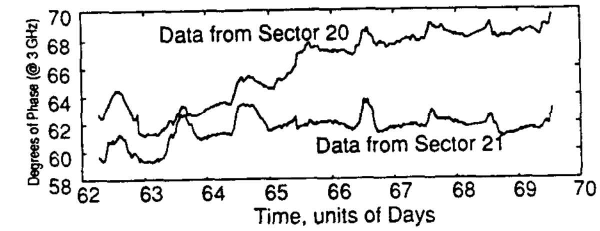

Fig. 3: History plots of PRL detector data. The data from three adjacent sectors represents changes originating in the individual sector's RF distribution and multiplication system, or in changes in the length of the PRL line itself. PRL changes show up in a single plot, while distribution changes present complimentary modulations on the phase detector data. Both effects are present.

The data contains signals which are the result of changes in one sector's PRL, and changes which are related to changes in the RF distribution and multiplication system; the former presents changes in the later sector's plot, while changes in the RF distribution and multiplication system present complimentary modulations on the data.

Effects common to both phase reference lines (*e.g.:* temperature changes) show up as similar modulations, in both sign and magnitude. Changes in a single RF distribution system (*e.g.:* instabilities in the frequency multiplier) show up as complimentary modulations, with opposite sign and identical amplitude; changes common to both systems aren't visible in these studies. All such modulations are present on the presented data.

The PRL is packaged is an insulated water jacket, and hung from the ceiling with aircraft cables. Figure 4 shows a detail and cross section of the packaging. Two copper water pipes are nested inside each other, with end adapters allowing water flow between the pipes as shown. The pipes have standard industrial pipe insulation; the coaxial cable is placed inside the smaller pipe, and the assembly is hung in place.

The PRL has proven to be quite sensitive to diurnal changes in the length of the steel support structures used to support plumbing and cable trays. All of the reference lines at SLAC have been re-installed, using steel aircraft cable to hang them from the gallery ceiling. By hanging the line with no longitudinal constraints, the daily length changes have been reduced from around 30° (@ 3 GHz) per 100 m of line down to typically less than 5°.

The Subdrive Line System

Within each sector is a small (1.75 inch) rigid coaxial waveguide used to deliver the high-power pulsed drive signal from the subbooster to each main klystron in the linac. As part of the instrumentation upgrade for the SLC, PRL and phase and amplitude detectors have been installed to monitor and allow the control of each RF source. As a result, there is no long-term stability requirement on this once-critical element.

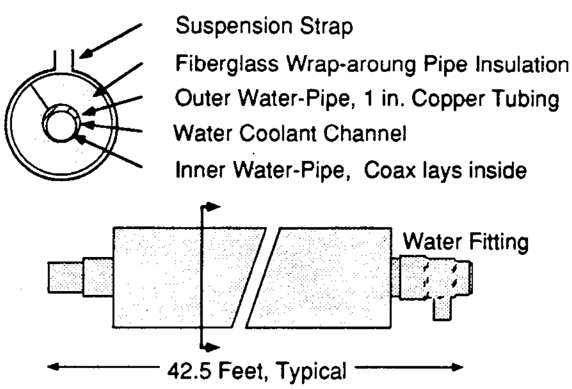

Fig. 4: Detail of the PRL insulation package. Each line segment consists of a length of temperature-stable 1/2-inch semirigid foam Heliax, surrounded by a water jacket and conventional water line insulation. Lines are suspended on cables to decouple changes in building length due to ambient temperature changes from phase length of reference line.

CONCLUSIONS AND RECOMMENDATIONS

With the use of interferometry as part of an active feedback, and using the phase and amplitude detectors to keep all RF devices correctly phased, the long-term stability of the Stanford Linear Accelerator seems to just meet the needs and requirements of the SLC.

There are a number of lessons to be learned, and examples to consider as design issues for the next large accelerator project. Higher frequencies, longer distances, and lower emittance specifications require that the next generation of engineers produce a accelerator with an intrinsically more stable RF distribution system.

The Main Drive System

By whatever name, any accelerator needs a stable distribution system to provide the fundamental RF for the accelerating klystrons, or other such high-power devices used.

The MDL at SLAC has considerable sensitivities to both temperature and pressure, and is tolerable only through the use of an interferometer-based feedback system. Feedback can reduce the error of a distribution system if error is fundamentally small, but implementation often must make unwarranted assumptions about the uniform distribution of the measured errors.

Serious consideration should be given to this link. A coaxial cable constructed with a vacuum dielectric will reduce the temperature sensitivities by a factor of two; further changes may result from choosing better supporting technology for the central conductor. Teflon dielectric is an especially poor choice where high power and temperatures are not a consideration, since it passes through two significant second-order crystal transitions near the usual operating temperatures.

Glass fiber optics systems are now available to support RF uses into the multi-GHz range. These include single-mode fibers, GaAs receivers and laser diodes, all or some of which are being developed for telephone communications. While this option is very exciting, and presents a very low loss option, the typical dielectric delay of any glass fiber optic line is around 40%, compared to 0.25%. This requires that the temperature phase stability of the glass be two orders of magnitude better just to compete with the air-filled rigid coax. A fused silica single-mode fiber should have a phase length change due to thermal dielectric changes of 150°C (@ 3 GHz) per 3 km! Interferometry will be required on these lines, and it will be necessary to remove errors with complete accuracy.

Modulated laser light through a vacuum-filled pipe is a very interesting option. Such a system is very stable, and would not depend on any interferometry to achieve phase stability. This can be achieved using a 0.5-m-diameter evacuated light pipe running the length of the linac. An RF source can be polarization modulating a laser shining into the pipe at one end, and small mirrors at each local sector can extract some fraction of the light into a high-speed photodetector. The same considerations regarding decoupling the thermal expansion of the pipe from the location of the detectors exists for this system as apply to the SLAC MDL. The mounting and safety considerations of such an extended vacuum system are rather frightening, and deserve attention.

Local RF References

Between each RF source, there should be a high-stability phase reference system. The SLAC model has satisfactory performance specifications, if: the length of the sector is limited to around 100 m, the cable plant is adequately isolated from the building, and errors of 5° (@ 3 GHz) are tolerable. Further improvements beyond the SLAC performance might include better insulation, temperature regulation, and higher water flow rates.

Beam Phase Detectors

Beam phase detectors prove to be promising tools in studying and possibly correcting any long-term system changes. These detectors use the beam itself as the primary diagnostic reference. Periodically, resonate cavities are installed in the beam's path, and the shock excitation RF signal from the beam is compared in phase with the local phase reference line.

Such detectors currently are being developed and commissioned at SLAC. The resonate cavity tuning is a critical parameter, as any small frequency error aliases as phase errors in the phase detector. These detectors are of no use in turning on a machine from scratch, being dependent on a beam, but may play a larger role in understanding the performance of various systems.

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1 R. B. Neal, ed., *The Stanford Linear Accelerator* (W.Benjamine, Inc., New York, 1968).

2 H. D. Schwarz and J. Vancraeynest, "Master Oscillator Stability Requirements Considerations," SLAC "SLC Note" CN-334 (1986).

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4 K. A. Thompson *et. al.*, "Feedback Systems in the SLC," *Proceedings of the 1987 IEEE Particle Accelerator Conference*, pg. 748, SLAC-PUB-4217.

5 Andrew Corporation, Orland Park, IL.

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