PROGRESS IN L-BAND POWER DISTRIBUTION SYSTEM R&D AT SLAC*

Christopher Nantista, Chris Adolphsen and Faya Wang, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract

We report on the L-band RF power distribution system (PDS) developed at SLAC for Fermilab's NML superconducting test accelerator facility. The makeup of the system, which allows tailoring of the power distribution to cavities by pairs, is briefly described. Cold test measurements of the system and the results of high power processing are presented. We also investigate the feasibility of eliminating the expensive, lossy circulators from the PDS by pair-feeding cavities through custom 3-dB hybrids. A computational model is used to simulate the impact on cavity field stability due to the reduced cavity-to-cavity isolation.

INTRODUCTION

In high energy particle accelerators, particularly in high-gradient linear collider designs, there is generally a significant mismatch between the peak power and pulse length in which RF can be efficiently produced and that in which they can be efficiently used for acceleration. The waveguide network connecting the sources to the structures, or power distribution system (PDS), is thus often less straight-forward than might be thought. Sources might be combined for convenient transport, sometimes compression techniques are used to trade pulse width for peak power, and power division at the accelerator for feeding multiple structures is usually required.

For L-band (1.3 GHz) superconducting linacs, state-of-art klystrons can produce 10 MW in 1.6 ms pulses, and state-of-the-art cavities can sustain gradients corresponding to about 300 kW of input power. Thus one source can drive quite a few cavities, 26 in current ILC plans, with allowance for losses and overhead for low-level RF control. The most direct approach to implementing this, adopted at DESY's TTF, is to use a set of hybrid directional couplers connected in series, each with a different coupling. Another approach, less compact, would be to use successive splitting in a branching arrangement.

In an inter-lab R&D collaboration, SLAC is providing RF system components for the test accelerator under construction in Fermilab's NML building, eventually a full system including couplers, but initially a PDS for the first cryomodule. The layout we chose [1] uses two levels of splitting (as does that chosen for the European XFEL), so that an appropriate portion of the power flowing in a main waveguide line is tapped off and then evenly split for each successive pair of cavities.

The two unique features of our PDS are the use of a novel variable tap-off (VTO), a four-port directional coupler with mechanically adjustable coupling [2], and the use of a four-port hybrid rather than a simple "T" for the binary split. The former allows uniform fabrication of the main line tap-offs as well as the ability to better optimize the overall gradient by tailoring the power distribution to accommodate a spread in sustainable gradient among the cavities [3]. The use of a 3-dB hybrid, standard for feeding standing-wave normal conducting accelerator structures, for the final split allows the reflected power from each cavity pair to be directed to a load. We hope thus to eliminate the need for an expensive and lossy circulator for each cavity.

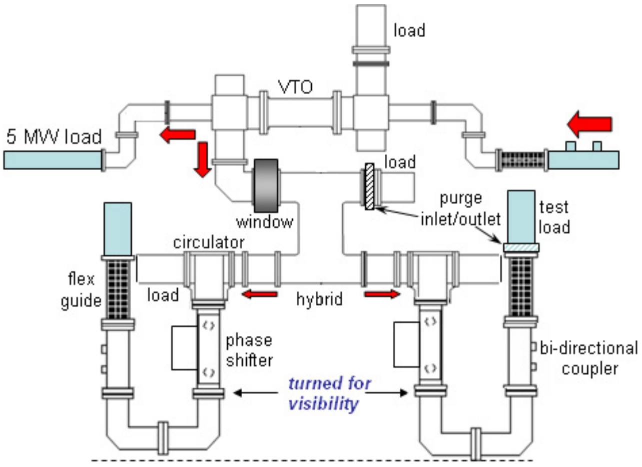

Figure 1: A two-feed sub-unit of the power distribution system. Blue components belong to the test setup, not the unit. The U-bends at the bottom are actually perpendicular to the page.

THE PDS UNIT

The pair-wise feeding in our approach is well suited to standard 8-cavity cryomodules. The local PDS along such a cryomodule consists of four, two-feed modular units connected in series. Fig. 1 shows a diagram of one such unit as built for FNAL. The VTO and the hybrid are SLAC designs, machined from aluminum and dip-brazed. The WR650 waveguide bends, spool pieces and semi-flexible sections are supplied commercially with custom lengths, many thick-walled for pressurizability. The remaining components were developed for DESY's L-band program by commercial vendors. They include a modified pillbox window to separate pressurized and non-pressurized regions, 1 MW loads, circulators (isolators), phase shifters and diagnostic directional couplers. Most flange connections employ aluminum gaskets combining knurled contact surfaces with rubber pressure seals.

The assembly is supported for testing and shipping in an aluminum box frame as shown in Fig. 2. Only one wall of this frame will remain after anchoring it in the accelerator enclosure. The upper waveguide, which would

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transport up to 3.5 MW in the ILC, is to be filled with pressurized N_2 to 2 bar absolute (14.5 psig) to suppress RF breakdown. The lower power region after the window is to be lightly purged with N_2 to avoid oxidation.

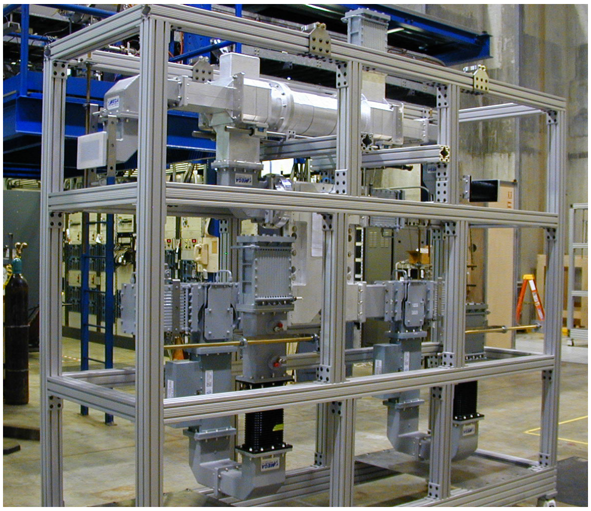

Figure 2: A two-feed sub-unit of the power distribution system in its support frame. When installed, the front wall of the frame will be removed, and the U-bends reversed to go under the remaining wall.

TESTING

The modularity of our PDS makes it convenient to individually test the two-cavity units. One unit has been completely tested and received by Fermilab; three more are in queue to be connected to our 5 MW klystron.

Low Power

The first unit tested has the VTO set for roughly 50% extraction. Cold test measurements were made first with a network analyzer. Fig. 3 shows the S matrix parameters between the input port and the other ports; 50.7% is transmitted, and 23.4% and 23.6% are extracted to the cavity feeds. The return loss is -43 dB (-38 dB from the output end. Of the approximately 2.3% missing power, most can be attributed to the corrugated flex guides and the circulators. The match at the two cavity feed ports is -23–26 dB and the isolation between them -69 dB.

The phases of the extracted signals differ by less than 2°, and the error in the through-signal phase (designed to be zero) is ~-6.7°. Such errors are easily corrected by the phase shifters.

High Power

After RF leak checking and connecting the cooling water circuits, the unit was configured for high-power operation by adding loads to the output ports and a directional coupler to the input port, as shown in Fig. 1. The lower region was N2 purged and the upper region pressurized to 12 psig.

To limit breakdown damage, the RF power was interlocked to trip off on a reflected signal from the unit. The VTO and hybrid had both been previously high-power tested successfully above 4 MW under 3 bar absolute pressure down to atmospheric pressure. We were more concerned about the circulators and phase shifter since we had not tested them and were pushing them somewhat beyond the level where they been reported to breakdown on occasion at DESY. Since the circulators absorb any reflected power from downstream breakdowns, we also interlocked on missing energy signals formed by comparing the forward signals at the feed directional couplers with the forward signal into the unit.

Power was gradually stepped up to at least 1.5 MW in 1.2 ms long pulses (our maximum pulse width) so each feed saw at least 360 kW (~10% more than needed for 35 MV/m, 9 mA acceleration at ILC). At this power, each phase shifter was run over its full 100° range. The dummy loads representing the cavities were then replaced with shorts to simulate worst case full reflection, and the above procedures were repeated. The feed arms have different lengths so the standing wave pattern in one arm was shifted a ¼ wavelength relative to that in the other, and any weak points in the components were guaranteed to see field. Finally ~24 hours of operation (at 5 Hz) were logged in this configuration to test reliability. No RF breakdowns in the PDS unit were detected during any of these tests (which we attribute in large part to having good RF connections between flanges).

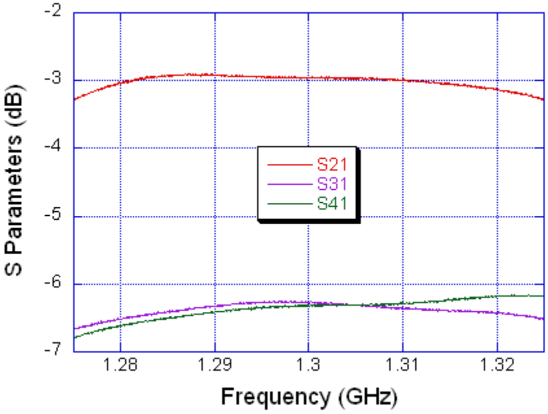

Figure 3: Network analyzer measurements of the coupling from the input port to the through port (S21) and to each cavity feed port (S31 and S41) for the first two-feed unit tested.

VTO SETTINGS

The four VTO's have been set for roughly the nominal tap-off ratios, i.e. 1/4, 1/3, 1/2, and 1. To account for transmission loss between one unit and the next, and to tailor the distribution for a given set of cavities, it can be shown that the couplings should be reset according to

$$C_n = \frac{G_n T^{N-n}}{\sum_{m=0}^{N-n} G_{N-m} T^m} \, , \qquad (1)$$

where T is the power transmission factor per sub-unit (not counting the tapped-off power), estimated from measurements to be ~ 0.986 for our system, and the G_n's are the relative gradients or powers at which each pair of cavities is to be run (lowest of the two thresholds). This is done by setting the angle of each VTO central section relative to the end sections to

$$\alpha_n = \frac{1}{2}\sin^{-1}\sqrt{C_n}\,. \qquad (2)$$

Such adjustment can be done in situ, with power locked out and the system depressurized, by loosening the two rotatable flange joints flanking the central section until it can be turned. This may also require unbolting the joint between E-plane bends at the VTO input end. The power distributed to each cavity pair is given by $P_1=P_0T_EC_1$ and

$$P_n = P_0 T_E \prod_{m=1}^{n-1}(1-C_m)T^{n-1}C_n \quad ,n>1\,, \qquad (3)$$

where P_0 is the power at the PDS input end and T_E the power transmission factor for the extracted power from the sub-unit input to cavity coupler (not counting through power).

OPERATION WITHOUT CIRCULATORS

Because the cavity spacing in the first FNAL cryomodule does not allow for both beam acceleration and combining reflections in the terminated hybrid port (the phase requirements conflict), circulators had to be included in this PDS. We have, however, procured custom H-plane bends to replace the circulators for an experiment powering the cavities without them (no beam). For this, the E-plane bends composing the U-bends in the feeds (see Figs. 1&2) will be reconfigured (one long and one short, rotated 90°) to produce equal phase lengths.

In addition to the reflection cancellation, which will require setting the cavity couplers for identical loaded quality factors, we can check the stability of the cavity fields. One concern with such operation is that the cavities won’t be as isolated as with circulators and resulting coupling between cavities will cause beating of the field amplitudes.

To allay such fears, we have simulated the effect of coupling between a pair of cavities driven through a hybrid with imperfect isolation. The cavities are assumed to be identical, with nominal ILC parameters, and the transient behavior of the field amplitudes was numerically computed from a set of coupled differential equations, including beam loading. The amplitude of the coupling was varied with zero and π/2 relative phases, and the resulting cavity gradients are shown in Fig. 4. The deviations from flatness along the bunch train tend to cancel between the two cavities, especially for the π/2 phase case, where they are largest. Similar results were reported in [4].

Measurements of the SLAC hybrids show isolations of -45.5–48.2 dB, while that in a commercial hybrid was measured to be -42.5 dB. With isolations better than -40 dB readily achievable, the affect on the cavity gradients should be negligible. Indeed, the fractional net gradient spread at this coupling level ranges from 0.9–6.5×10^{-5}, depending on phase.

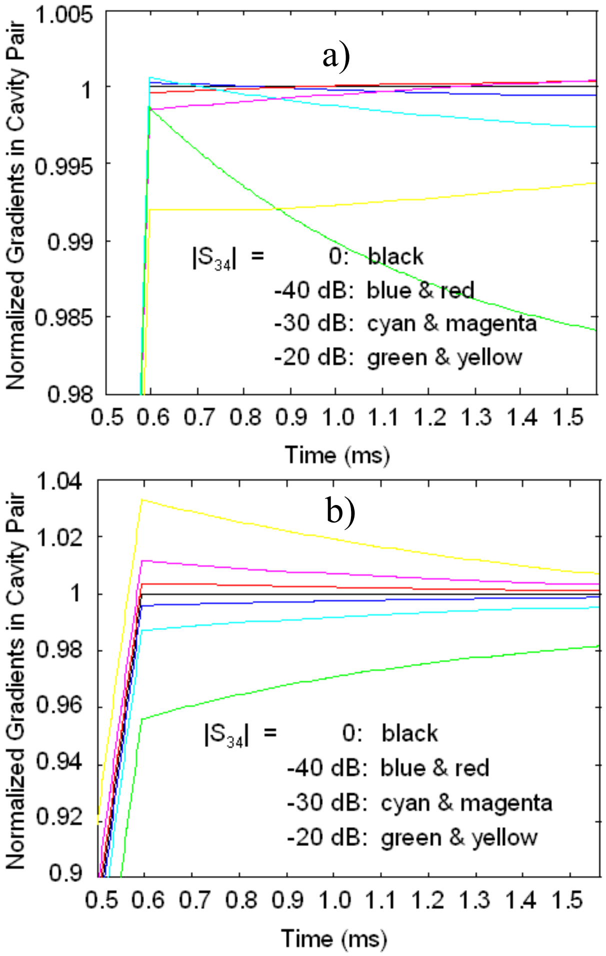

Figure 4: Simulations of cavity field amplitude “flat-tops” with imperfect isolation between hybrid-coupled cavities at coupling phases a) 0 and b) π/2. Pairs of colors represent the pair of cavities.

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