A HIGH POWER DUAL RESONANT RING SYSTEM FOR HIGH GRADIENT TESTING OF 11.424 GHz LINEAR ACCELERATOR STRUCTURES*

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Abstract

The salient features and design parameters of a dual resonant ring system configured for evaluating the high gradient performance of 11.424 GHz TW linear accelerator structures are presented; and the inherent rapid protection mechanism that automatically limits energy deposition during breakdown of the structure, and minimizes RF source reflections, is discussed. The diagnostic characteristics of the RF bridge load monitors and their unique capability of detecting the power imbalance caused by a feedback loop phase change of less than 2 parts in 10^4, representing a 2 to 3 degree phase change of the linac structure, is described. The transient and steady-state power apportionment within the ring system is analyzed; and, in considering initial high power tests using an 18-cavity CLIC/KEK/SLAC structure, the results indicate that the demonstration of an unloaded average accelerating gradient of 108 MV/m will require a source power of 26 MW.

INTRODUCTION

A resonant ring power amplification concept using an RF bridge to recirculate the feedback power from a linac structure was first proposed and demonstrated at AERE [1] in 1948, and was instrumental in the immediate development of gantry mounted, megavoltage radiotherapy linacs. In the decades that followed, resonant ring systems continued to evolve and to be applied to a variety of linac applications. Briefly described, Figure 1 shows a four port RF bridge with arms 1, 2, 3 and 4, at power levels P_S, P_A, P_F and P_L, connected to the RF source, the linac input, the linac feedback and an RF load, respectively. A variety of high power RF bridge circuits, including waveguide hybrid junctions and short branch couplers, have been used for these applications and designed so that the following conditions are satisfied: arms 1 and 3 should be independently matched to the bridge when arms 2 and 4 are terminated by their characteristic impedance; arms 1 and 3 should be highly isolated so that power fed into either arm is transmitted to loads in arms 2 and 4 only; conversely, arms 2 and 4 should be balanced so that power entering either arm is delivered to loads at arms 1 and 3 only; and there should be no power recirculating within the bridge. For a feedback loop having an integral number of wavelengths, and for a bridge ratio n, when correctly phased feedback power (P_F) from the linac structure is combined with the source power (P_S), after an initial transient build-up

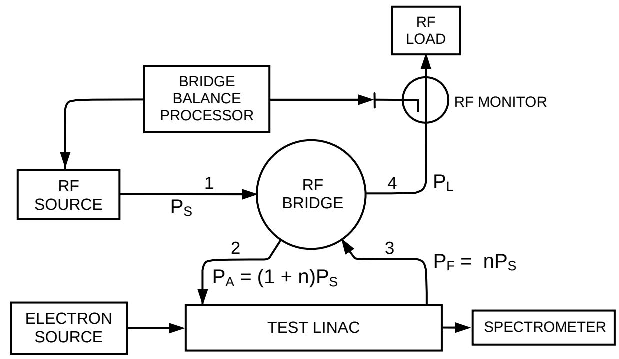

Figure 1: Typical four port RF bridge configuration for a resonant ring linac test facility using phase lock feedback control.

period, a steady-state power level of P_A=(1+n)P_S will appear at the linac input, and the load power (P_L) will be reduced to zero.

More recently, a modified version of the concept using dual resonant rings was developed for evaluating the high gradient performance of 17 GHz dual feed linac structures; and test results have shown [2] that the resonant ring system not only provides power amplification benefits, it offers a unique rapid response, automatic protection mechanism that minimizes the RF source reflection and limits the energy deposition during an RF breakdown in the linac structure. When a structure breakdown occurs, the ring recirculating power is instantly interrupted causing rapid truncation of the linac input power (P_A), and simultaneously, the incoming source power (P_S) is redirected into the bridge load (P_L) for the remainder of the klystron pulse, as indicated in Figures 2 and 3. The same biconjugate property of the bridge isolating the RF source from the ring spill feedback during a structure breakdown also ensures that the RF source is presented with a constant impedance during the RF power build-up process.

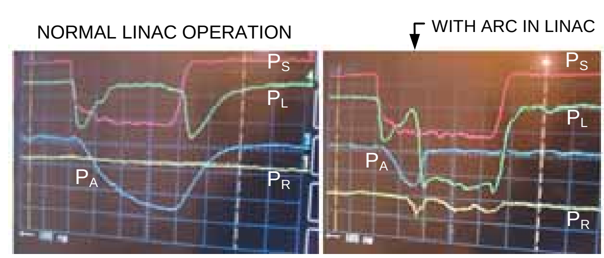

Figure 2: 50 ns/div waveforms showing, during a structure breakdown, rapid termination of the linac power (P_A) and transmission of the source power (P_S) to the load (P_L). (P_R is the linac reflected power signal.)

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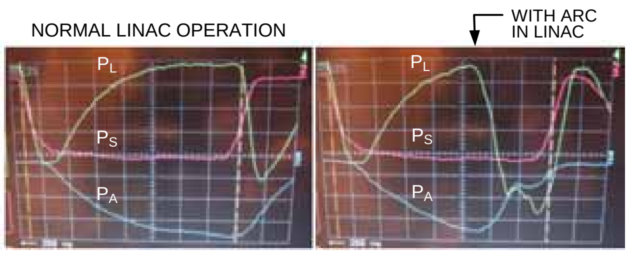

Figure 3: 20 ns/div waveforms of the fast redirection of source power to the load during a self-quenching breakdown in the structure.

11.4 GHz RESONANT RING SYSTEM

The contention that the inherent fast response protection of a resonant ring system may be an independent and important contributing factor toward achieving higher gradients, and the difficulty of accurately assessing that factor, emphasized the need for directly comparing the performance of a TW linac structure when driven by a resonant ring and when load terminated and directly excited by an RF source. The extensive compilation of 11.4 GHz test data and the established protocols at the SLAC test facility presented a unique environment for this comparative evaluation; and the recent selection of T18, an 18-cell, highly tapered group velocity structure [3,4], as a candidate test linac enabled a dual resonant ring system to be designed for matching the insertion loss, filling time and electrical length of the T18 circuit and associated input and output RF feed and mode launching assemblies.

Although accurate values of the T18 structure flange to flange phase length and insertion loss are yet to be measured, existing S-parameter measurements inclusive of the cold test components, and 3D EM simulations of the mode launchers, provided sufficient input data for the resonant ring design study. Initial investigations using overcoupled resonant rings confirmed that, while the power build-up time could be reduced by 50 percent, as shown in Figure 4, the loss of overall gain and the bridge load power imbalance were not acceptable trade-offs compared to operating with a critically coupled ring.

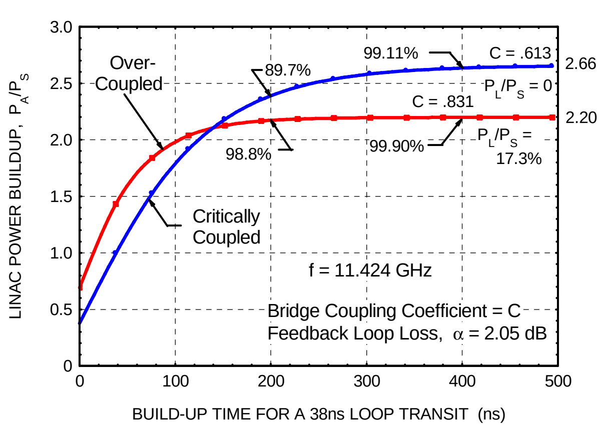

Figure 4: Comparison of linac power buildup for a critically coupled (C=.613) and an overcoupled (C=.831) resonant ring having a feedback loop loss of 2.05 dB.

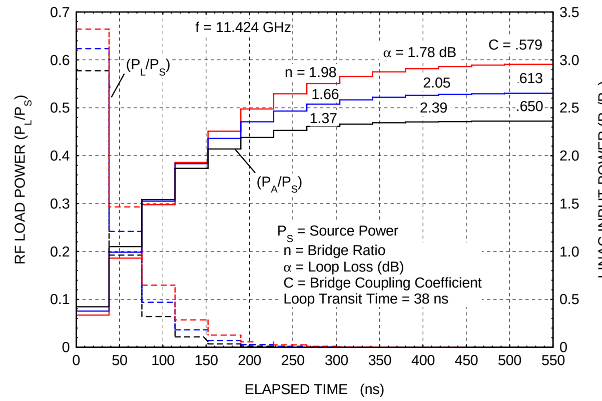

Figure 5: Linac input power (P_A/P_S) buildup and load power (P_L/P_S) decay for critically coupled resonant ring systems having bridge ratios of 1.98, 1.66 and 1.37.

The linac input power buildup and the load power decay characteristics for a range of critically coupled resonant ring design parameters are compared in Figure 5 with the chosen design values of n=1.66, α=2.05dB and C=0.613 that give a power buildup of 2.66.

The dual ring system was configured to have multiple pumping ports, readily removable high directivity directional couplers (so the same diagnostics can be used for the direct excitation structure tests), compact hybrids, and the capability of resonating each feedback loop at the precise operating frequency of the test linac.

A layout of the proposed 11.4 GHz dual resonant ring system, and the steady-state power apportionment required for operating the T18 structure at an unloaded average accelerating gradient of 108 MV/m, are shown in Figure 6; and a summary of the system design parameters, based on the estimated electrical lengths of the ring components, is given in Table 1.

Table 1: Design Parameters of an 11.4GHz Dual Resonant Ring System Configured for High Gradient Testing of the CLIC/KEK/SLAC (T18) Linac Structure

System Operating Frequency	11.424	GHz
Test Linac Attenuation Parameter (τ)	0.21	Np
Test Linac Harmonic Mean Group Velocity $(v_g)_{hm}$	0.016	c
Total Loss in Feedback Loop (α)	2.05	dB
Resonant Ring Transit Time	38	ns
Resonant Ring Total Phase Length	17280	deg
Resonant Ring Phase Dispersion	15	deg/MHz
WR90 Rectangular Waveguide Phase/Length Relationship	11.2	deg/mm
WR90 Rectangular Waveguide Length/Phase Relationship	.089	mm/deg
RF Bridge Ratio $[n=(T_C/C)^2]$	1.66	
RF Power Buildup (n+1)	2.66	
RF Bridge Transmission Coefficient $\{T_C=[n(n+1)]^{1/2}\}$	0.790	
RF Bridge Coupling Coefficient $[C=(n+1)^{-1/2}]$	0.613	
Unloaded Average Accelerating Gradient . .	108	MV/m
RF Source Power	26	MW
Linac Steady-State Input Power (P_A)	65	MW

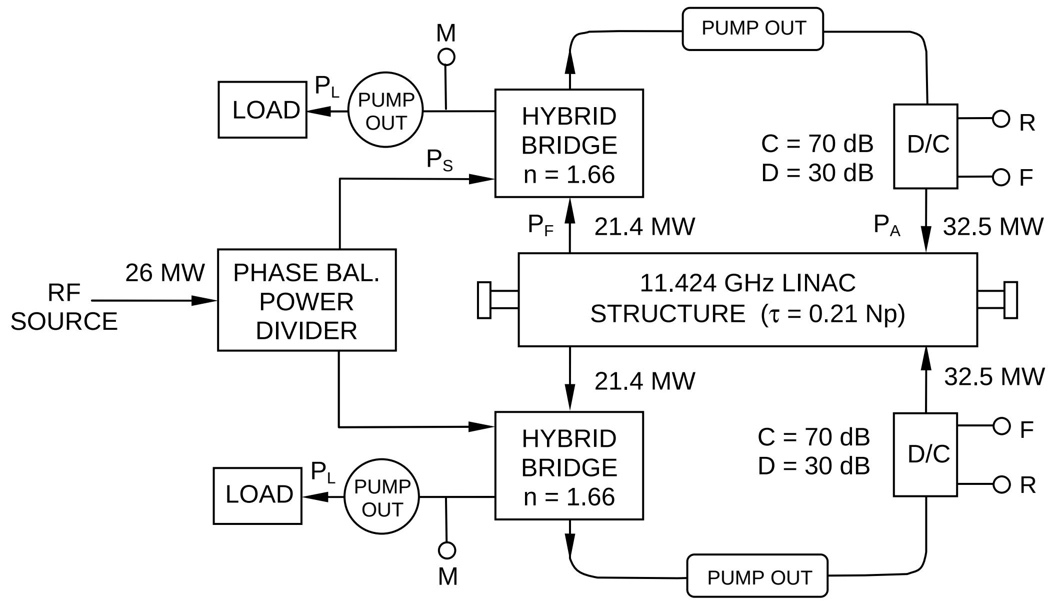

Figure 6: An 11.424 GHz dual resonant ring system with an embedded CLIC/KEK/SLAC (T18) linac structure showing the power distribution required for operation at an unloaded average accelerating gradient of 108 MV/m.

BRIDGE LOAD POWER MONITOR

Because the steady-state zero power flow to the load is the result of maintaining a balanced bridge condition using a phase dependent, precise cancellation and reinforcement of power in the load and linac input arms, respectively, the amplitude of the load monitor signal has a very sensitive response to a small change in phase of the power recirculating through the linac structure. The phase discriminating effectiveness of the bridge load power monitor, identified as M in Figure 6, is shown in Figure 7; and the data indicate that a phase change of only 2 or 3 degrees in the linac structure, representing less than 2 parts in 10^4 of the feedback loop length, results in a readily detectable power imbalance equal to approximately ½ percent of the source power. In commercially developed resonant ring X-band linacs, this unique feature enabled an automatic phase lock control system (refer to Figure 1) to maintain stable performance of a megavoltage photon beam during 100°C ambient temperature variations [5]. The Figure 7 data also show that ±¼ dB variation of the feedback power has a negligible effect on the bridge balance offset level, indicating that the ability to detect small phase changes in the linac test structure, during high gradient processing, for example, will be unaffected by the power variations normally encountered in practice.

Because the input power of a ring driven linac is dependent on both the amplitude of the source power and the phase of the recirculating power, assurance of a high quality beam requires the resonant ring dispersion to be consistent with the tolerable phase error. For the proposed 11.4 GHz ring system, the computed linac input power reductions caused by feedback phase errors of 2, 5 and 8 degrees are 0.2, 1.25 and 3.15 percent, respectively.

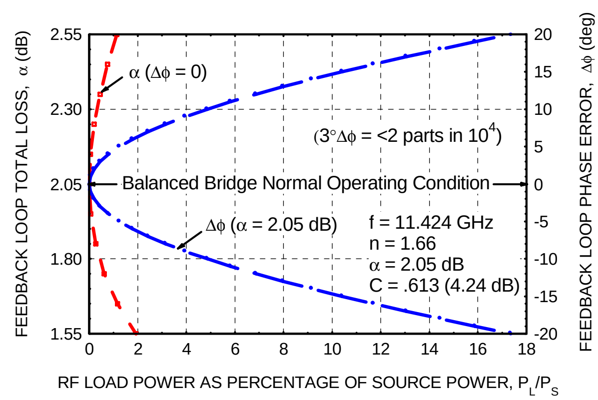

Figure 7: RF bridge load monitor computed response to power imbalance caused by a change in phase or attenuation of the linac feedback loop.

ACKNOWLEDGMENTS

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