CLOSE-COUPLED RF POWER SYSTEMS FOR LINACS

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Abstract

Close-coupled rf (CCRF) power systems for accelerator applications have been developed and tested. Prototypes, based on Eimac Planar Triodes (Y-690 and YU-176) in grounded-grid configurations, exhibit outstanding performance, efficiency, gain and simplicity. These units mount directly on the side of the accelerator and operate in an extension of the accelerator vacuum, thus eliminating many components of conventional rf power systems such as rf output resonators, transmission lines, and vacuum windows. Rf power is coupled to the accelerator through a loop operating at the anode potential. Cooling for the anode is provided through the coupling loop. After passing through the loop, the rf currents are shunted to ground through an integral rf-bypass capacitor. This same approach is relevant to larger tubes, offering peak powers in the 0.5-1.0 MW region, with all the same advantages, including substantial weight savings.

Introduction

High-strength, radio frequency, electromagnetic fields, bounded by resonant cavities, are commonly used in particle accelerator systems to accelerate, deflect and/or focus charged particle beams. The rf power required to create and sustain these fields is traditionally obtained from external rf power sources connected to the resonant cavities through some sort of rf power transmission lines and rf power coupling devices. These conventional distributed systems for powering rf devices in accelerator systems are unnecessarily complex and expensive.

A reduction in the cost and complexity of these systems would have a substantial effect on the viability of accelerator systems for medical, industrial, scientific and defense applications. One approach to this goal would be to develop a close-coupled rf power source where the active element of the rf power source mounts directly on the resonant cavity and interacts directly on the rf fields within the cavity. This could eliminate many components and functional interfaces of conventional rf power systems, resulting in simpler, less expensive, more compact, and more reliable accelerator systems for a variety of applications.

Close-Coupled RF Power Systems

Close-coupled rf power (CCRF) systems for accelerator applications are under development at SAIC. Prototypes of these systems, based on the Varian/Eimac planar triodes in grounded-grid, cathode-driven configurations, exhibit outstanding performance, efficiency, gain and simplicity. These units are designed to mount directly on the side of an RFQ linac, in an extension of the linac vacuum, and coupledpower directly to the linac fields through a loop operating at the anode potential. Cooling for the anode is provided through the coupling loop. After passing through the loop, the rf currents are shunted to ground through a rf-bypass capacitor, which is an integral part of the design. These CCRF power systems promise to eliminate many components of conventional rf power systems such as rf output resonators, rf output couplers, rf power transmission lines, and rf power windows.

Schematics for both conventional rf power systems and close-coupled rf power systems are shown in Fig. 1. In the conventional arrangement, power amplifier optimization and impedance matching to the resonant load are based on measurements of the forward and reflected power in the transmission line and the efficiency of the power transfer from the transmission line to the accelerator. They do not, however, indicate the amount of rf power actually generated by the power amplifier or the amount of power lost in the amplifier output circuits.

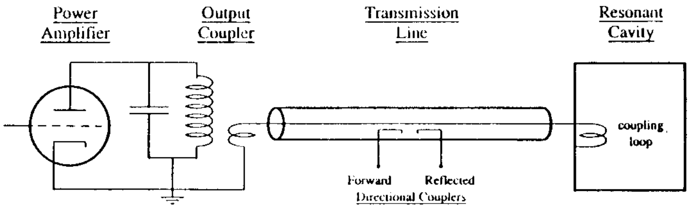


Fig. 1a. Conventional RF Power System.

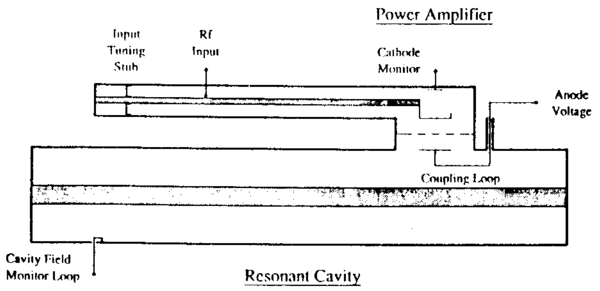


Fig. 1b. Close-coupled RF Power System.

In the close-coupled arrangement, there is no direct way to separate the performance of the power amplifier from the performance of the power coupling device. The concept of forward and reflected power, between the power amplifier and the resonant load, is not applicable. Hence, alternate techniques have been developed for system optimization. The only relevant measure of the system performance is the magnitude of the resonant fields, which, after all, is the principal reason for the system.

In order to optimize the performance of a close-coupled rf power system, there are several portions of the system that must be properly tuned and/or matched. The data available for these operations include the forward and reflected power of the rf input drive line, the cathode excitation, the cathode bias, the anode voltage and current, and the magnitude of the fields in the output resonator. The variables effecting these data are the position of the input resonator tuning stub, the position of the input resonator drive tap, the cathode bias (determined by selection of zener diode), and the size, shape and orientation of the coupling loop that couples the anode current to the magnetic fields of the resonant load.

The procedure for adjusting these variables to effect the optimum performance includes: 1) adjusting the rf drive frequency to the resonant frequency of the resonant load (or alternatively, adjusting the resonant frequency of the load to the drive frequency), 2) adjusting the position of the input resonator tuning stub and input resonator drive tap to achieve a minimum reflected power on the rf input drive line while maintaining a significant cathode plate excitation, and 3) adjusting the size, shape, and orientation of the coupling loop to achieve high efficiency ($\geq$70%) power transfer to the resonant load and a high power gain ($\geq$13 db) across the power amplifier as indicated by a measure of the magnitude of the resonant fields.

The Eimac planar triodes (Y-690, YU-141, YU-176) can produce peak rf power in excess of 20-30 kW with duty factors in the range of a few percent. They are rated for performance up to 2 GHz. They are small in size (one inch in diameter and two inches long) and reasonable in cost. They can be deployed in clusters for higher power requirements. A single cluster of 12 of these small tubes have produced as much as 360 kW of rf power for linac applications.

Planar triodes operate well, either singly or in clusters, in the grounded-grid, cathode-driven configuration. This implies that the anode and the coupling loop operate at elevated potential (6-10 kV) and should have considerable capacitance to ground (200 pf or more) for the rf currents. Using the required electrical insulation as the dielectric of the required rf bypass capacitor results in the compact and rigid configuration shown in Fig. 2. The anode cooling water enters the anode bypass capacitor ring, passes through the coupling loop to the anode cap, and then back to the capacitor ring on the way out.

Figures 3 and 4 suggest 4- and 8-tube configurations for powering RFQ linacs. The 8-tube configuration employs a pair of triodes in each CCRF module.

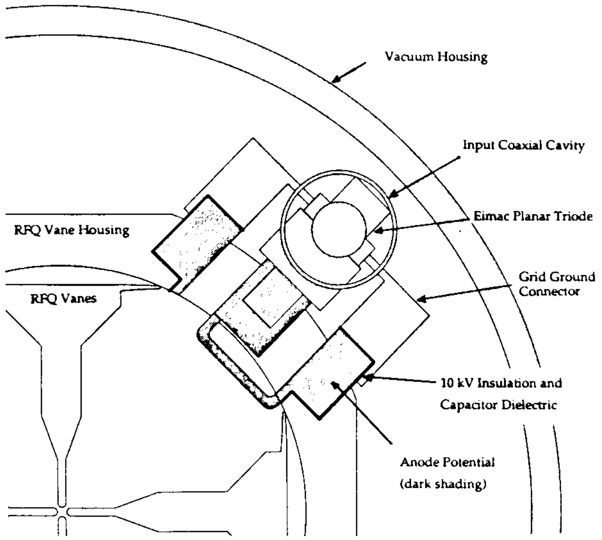


Fig. 2. Anode Loop Insulation and RF Bypass Capacitor.

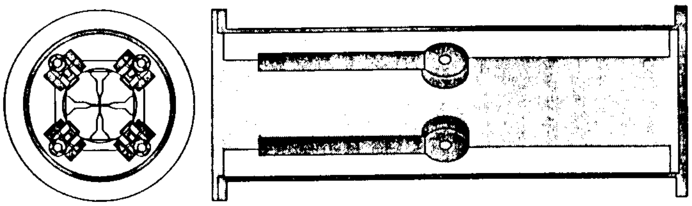


Fig. 3. Four-tube RFQ Configuration

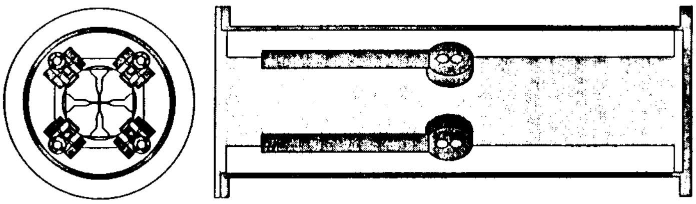


Fig. 4. Eight-tube RFQ Configuration.

Each triode or cluster of triodes (2 or more) requires a cathode excitation circuit, typically involving a resonant cavity or an impedance transformer. The configurations, shown in Figs. 3–5, involves a three-quarter wavelength coaxial cavity with the outer conductor grounded, a tuning stub at the far end, an adjustable tap for input coupling, and the open end of the center conductor connected to the cathode. The filament leads are routed through the center conductor of the input resonator so as to be at the same rf potential as the cathode.

Fig. 5 shows a two-tube, close-coupled rf power system coupled to a 425 MHz RFQ linac. The pair of planar triodes (YU-176) can produce in excess of 60 kW of peak rf power for 2% duty factor.

With many different input cavities, care must be taken to drive them in the proper phase so that their output powers will combine constructively They can either be driven as a plurality of coupled strip lines, a resonantly coupled chain, or through a power splitter and equal length lines. The preferred scheme will depend on the details of the configuration.

Applications

There are distinct advantages in powering linacs with a multiplicity of smaller power units, namely, it is relatively easy to survive the failure of any one unit by calling on some reserve power from the remaining units, and the system hardware, being small in size and large in number, results in favorable design and fabrication costs. Most analyses suggest high reliability and substantial cost saving for the close-coupled scheme over the conventional rf power systems.

For an RFQ linac requiring 100 kW of peak rf power, one planar triode in each quadrant, as shown in Fig. 3, represents a conservative and symmetrical configuration having ample rf power for normal operation, with sufficient reserve to survive the failure of any single power unit.

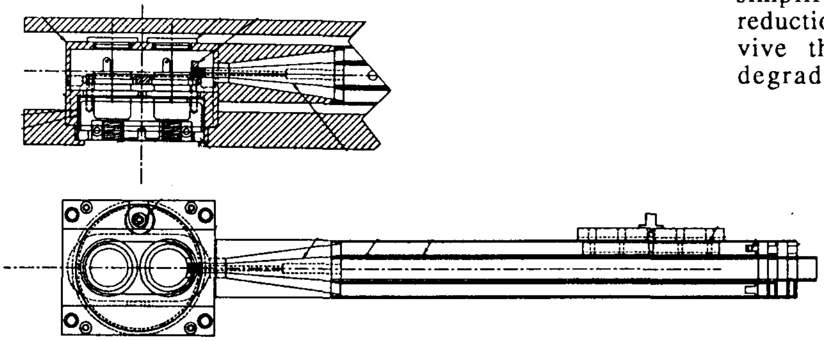
For an RFQ linac requiring 200 kW of peak rf power, a pair of planer triodes in each quadrant, as shown in Fig. 4, would provide ample power for normal operation, with sufficient reserve to survive the failure of several units. Each pair of triodes would be clustered together as a unit with their outputs combined into a single rf drive loop.

Drift tube linacs (DTLs), requiring many megawatts of power, could be driven by clusters of four planar triodes connected to each drive loop. These clusters need only be 4 inches in diameter. Ten such clusters could produce more than a megawatt. One cluster every 4 inches represents a linear power density in excess of 1 MW/m.

An array of small planar triodes could be used to power coupled cavity linacs (CCLs), even at frequencies that are typically higher than that of RFQs and DTLs.

Conclusions

Close-coupled, loop-driven, rf power sources, using the linac resonator itself as their output resonator and power combiner, offer substantial savings in the cost, complexity, weight, and efficiency of the rf power sources for linac applications. By integrating the rf power sources with the linac, much of the mystery of both entities is removed. All problems associated with the extraction of the rf power from the power source, transmission of the rf power to the linac, and injection of the power into the linac are solved, in the simplest way, by the close-coupled configuration. The system control is simplified by eliminating any concern over reflected power and standing waves in the nonexistant transmission lines. Such rf power sources are no longer a constraint on the linac frequency, since the major element of the rf system is the linac itself. The power source itself is essentially broad-band, delivering its power directly to the resonant load. The power efficiency is improved by eliminating the power dissipated in the conventional rf power output resonators, couplers and transmission lines. System reliability is improved by the general simplification of the system, the significant reduction in part count, and the ability to survive the failure of some power units (graceful degradation).



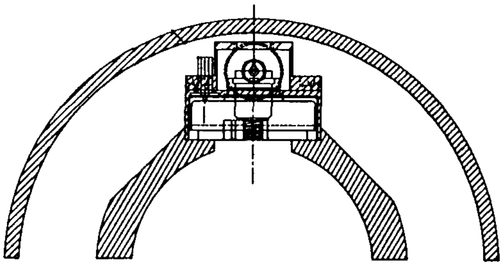


Fig. 5. Two-Tube, Close-Coupled RF Power System -- Mark III.