RF SYSTEM CONSIDERATIONS FOR LARGE HIGH-DUTY-FACTOR LINACS

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Abstract

RF systems are often a major cost item for linacs, but this is especially true for large high-duty-factor linacs (up to and including CW) such as the Accelerator for Production of Tritium (APT) or the Accelerator for Transmutation of nuclear Waste (ATW). In addition, the high energy and high average beam current of these machines (approximately 1 GeV, 100-200 mA) lead to a need for excellent control of the accelerating fields in order to minimize the possibility of beam loss in the accelerator and the resulting activation. This paper will address the key considerations and limitations in the design of the RF system. These considerations impact the design of both the high power RF components and the RF controls. As might be expected, the two concerns sometimes lead to conflicting design requirements. For example, minimum RF operating costs lead to a desire for operation near saturation of the high power RF generators in order to maximize the operating efficiency. Optimal control of the RF fields leads to a desire for maximum overdrive capability in those same generators in order to respond quickly to disturbances of the accelerator fields.

High-Duty-Factor Linacs

In the design effort for accelerator driven transmutation technologies (ADTT) the accelerators are generally high-current, high-duty-factor linacs. A selection of some of the ADTT applications is shown in Table 1. In all cases the current is 80 mA or more, the duty factor is CW, and the output energy is 800 MeV or more. The RF power in Table 1 is the amount of power needed for the accelerator, the beam, transport losses, and feedback control. In optimizing the accelerator for beam transport, each accelerator module requires a different amount of power. This makes the system very inefficient in its usage of the installed RF power.

Table 1
Current, Energy, and RF power for various ADTT options.

Type of Machine	Current (mA)	Energy (MeV)	RF Power (MW-CW)
Commercial Waste Transmuter	250	1600	500
Accelerator Production of Tritium	200	1000	255
Accelerator Based Conversion of Pu	80	800	110

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In one design example, the required RF power varies over the length of the accelerator by almost a factor of 2, and the installed RF capability is 40% above the required amount. Using this as a basis, the Accelerator Based Conversion of Pu (ABC) system, which needs 110 MW of RF power, will actually need approximately 154 MW of installed power.

In all of these linacs, because of the very high levels of beam power and the potential damage and activation which can come from beam loss, the beam losses must be on the order of 1 part in 10^6 (or better) over the whole accelerator. This has implications for many parts of the accelerator, but it specifically puts severe requirements on the RF feedback control system. The fields must be maintained at the proper phase and amplitude, despite disturbances on the beam and input power system.

An Example Accelerator

Figure 1 shows the basic layout of the accelerator for ABC. It uses an RFQ and Drift Tube Linac (DTL) for the lower energy acceleration (up to 100 MeV). The higher energy acceleration is then done by a Bridge-Coupled DTL (BCDTL) and a Coupled Cavity Linac (CCL) up to the final energy of 800 MeV. Table 2 shows the efficiency estimates for this system (from AC input to beam output). For 64 MW of beam power, the accelerator requires 200 MW of input AC power. To achieve this level of efficiency, the operating efficiency of the RF generators must be 58%, the beam loading must be 58%, and the transport losses (including cavity mismatches) must be 95%. These are all very difficult parameters to obtain but are achievable if a suitable multi-year development effort is undertaken for all parts of the RF system.

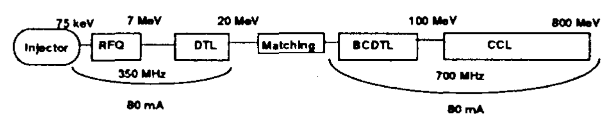

Fig. 1 Accelerator Concept for an ABC

Table 2
Power and Efficiency Estimates for ABC

Beam Power	64 MW
Structure Power	46.3 MW
AC Power Requirement	200 MW
RF to Beam Efficiency	58%
AC to RF Efficiency	58%
RF Transport Efficiency	95%
AC to Beam Efficiency	32%

RF Generator Operating Efficiency

The operating efficiency of the RF generator is a key issue. A 1% improvement in the DC-to-RF conversion efficiency of the generator in the above example would mean a reduction in operating costs of \$1 million per year (based on 6570 hours and 5¢ per kW-hr). Figure 2 shows the operating efficiency of a klystron and an Inductive Output Tube (IOT). The best feature of the IOT is that very little loss in operating efficiency occurs over an output power range from 50 to 100% of the tube maximum. The primary drawbacks to the IOT are the low gain (≈22 dB) when compared to the klystron (≈50 dB) and the consideration that it is unlikely that an IOT can be made with CW output capability much above 500 kW because of RF heating of the cathode by the input RF drive. The middle curve in Figure 2 shows the klystron saturated efficiency can be improved for reduced output levels by adjusting the klystron current with the modulating anode voltage. One should remember that the operating point (and therfore the operating efficiency) of the klystron would be 10% or more below this line to allow for feedback control.

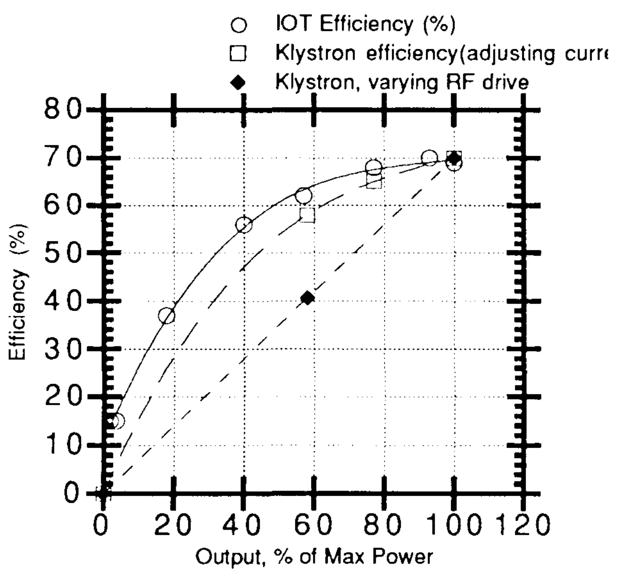

Fig. 2 Efficiency for a Klystron and IOT vs. % of Maximum Output Power

Availability

An added feature of these accelerators is the very high levels of required availability. To meet their design goals, most of the applications require plant operation for 75% of the year (6570 hours). This typically means that the accelerator must be available for 85% of the year, and the RF systems must be available more than 90% of the year. The 25% of the year during which the plant is not operational must account for all scheduled maintenance, unscheduled maintenance, and reduced performance operations (such as operation with reduced current). For a large CW proton accelerator, this is a very difficult task. Again, extensive development is needed to design an RF power system with diagnostics to indicate weak or failing components which can be repaired during a scheduled maintenance. This is crucial to minimize the unscheduled shutdown time. The well-diagnosed RF system must have: 1)redundancy of diagnostics to eliminate wrong information, 2)expert systems to supplement and guide operators, and 3)trend analysis of key variables to predict and anticipate failures.

RF Controls

The RF controls for a large CW proton accelerator represent a significant developmental effort although the risk should be minimal. The concepts and designs that were developed for the LANL Ground Test Accelerator program could be modified slightly for application to an ADTT accelerator. The RF field control can be accomplished with a combination of feedback and beam feedforward. The resonant frequency tracking can be accomplished with a reflection analyzer and use of a tunable RF source for heating the RF cavity during turn-on and fault recovery. The implementation for this equipment should be accomplished entirely with electronic circuitry to provide the most reliable system possible. Automation should be designed into the system to take advantage of modern digital processing capabilities that will eliminate the costly hands-on operator intervention.

While a pulsed machine presents a certain set of difficulties, the pulsed structure lends itself well to operations such as fast protect, adaptive feedforward, gradual startup, and many others. For a CW proton accelerator, it must be possible to turn on and tune up the accelerator from a variety of initial conditions, including first-time commissioning, cold starts after maintenance shutdowns, short interruptions caused by RF station faults, and extremely brief beam absences due to chopping or fast protection aborts. Figure 3 shows a simplified block diagram of a low-level RF system. This diagram depicts the fundamental components of the low-level RF system needed to perform two primary functions, field and resonance control. The field control electronics use a sample of the field in the RF cavity along with a beam feedforward signal to maintain the proper amplitude and phase in the RF cavity. The resonance detection electronics use the reflectometer signals to calculate the resonance condition of the RF cavity.

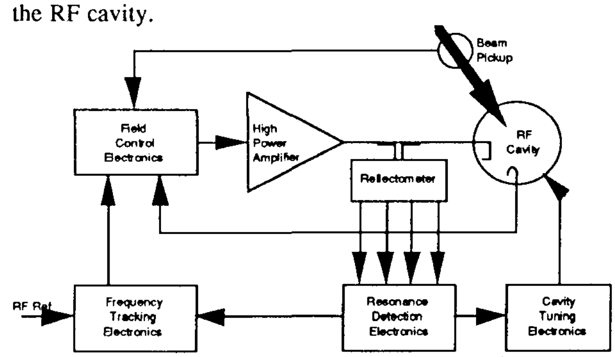

Fig. 3 Block Diagram of a low-level RF control system.

This calculated resonance condition is used for both frequency tracking and cavity tuning.

Feedforward in a Low-Level RF Control System

For a CW accelerator, disturbances do not repeat in any definable pattern. Implementation of feedforward must use a measured system input to predict errors in the output. In these heavily beam-loaded accelerators, beam-current fluctuation is the dominant disturbance to the RF field. Consequently, the amplitude and phase of the beam current are measured and used to derive feedforward correction functions that negate any errors in the RF field parameters before they occur. The system topology for such a beam feedforward implementation requires that a single beam diagnostic sensor just after the beam source be used to derive the feedforward signals for all of the RF cavities in the system.

The results of RF system simulations demonstrate that beam feedforward does enhance RF field regulation and that automatic gain adjustments are possible.

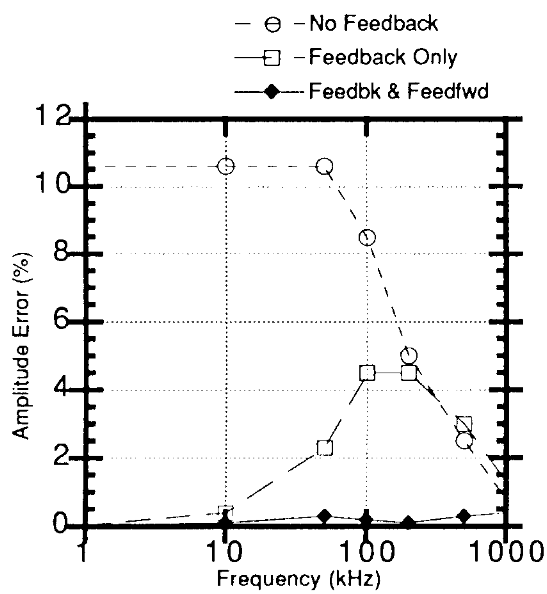

Fig. 4 Amplitude errors due to 20% beam noise with no feedback, feedback alone, and feedback combined with feedforward

Figure 4 shows the effects of beam current fluctuations of 20% on the RF field of a typical heavily beam-loaded accelerator cavity. Three control system configurations are shown: open-loop operation without a control system, regulation with a feedback control system, and combining both feedback and feedforward control systems. With both feedback and feedforward, the RF field amplitude and phase errors could be maintained at less than 0.5%/0.5° in the presence of beam current fluctuations of 20% at any frequency.

Generator Saturation Characteristics

For control of the RF fields in the accelerator, large gain in the RF generator system is necessary. Figure 5 shows the input/output amplitude characteristics of a typical klystron and IOT. The slope of these curves represent the generator gain. Note that the klystron achieves complete saturation. The slope (and therefore the gain) goes to zero at the maximum output of the tube. At saturation the control system is completely ineffective with amplitude errors, and even near saturation the control capability is compromised. In contrast notice that the IOT never reaches complete saturation. Even at the maximum output of the tube, a reasonable slope is evident. The control system is therefore more effective with the IOT when operating near the maximum output of the tube.

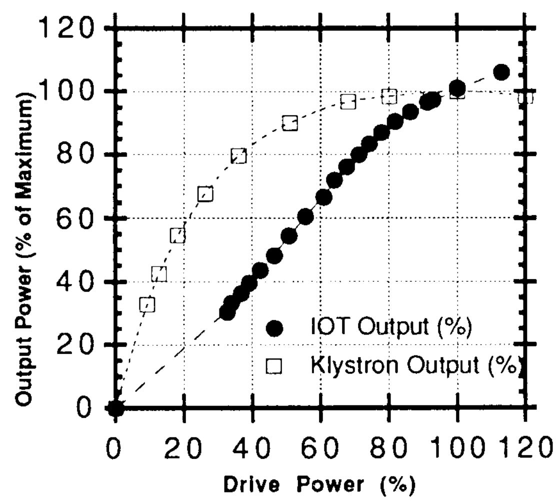

Fig. 5 Input/Output Characteristics of an IOT and a Klystron

Conclusion

High-Duty-Factor Linacs, such as those needed for ADTT applications, require very large amounts of RF power and a very high level of availability to accomplish their designated goals. In addition, as proton linacs, only a few of the RF modules can fail (at most, and only at the high energy end of the accelerator) before the entire accelerator must be shut down. The RF system designs for these applications require new developments in RF generators (maximizing the operating efficiency and reliability), new developments in system diagnostics and controls (optimizing the component availability), and new developments in low-level RF control systems (minimizing field errors, down time, and the need for excess generator power). These developments are difficult but are achievable if a suitable multi-year development effort is undertaken.