FIELD CONTROL IN A STANDING WAVE STRUCTURE AT HIGH AVERAGE BEAM POWER

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Summary

A 100% duty factor electron beam has been accelerated through a graded-β side-coupled standing wave structure operating in π/2 mode. Three non-interacting control loops are necessary to provide the accelerating field amplitude and phase and to control structure resonance. The principal disturbances have been identified and measured over the beam current range of 0 to 20 mA. Design details are presented of control loops which regulate the accelerating field amplitude to ± 0.3% and its phase to ± 0.5° for 50% beam loading.

Introduction

Many accelerator control systems are designed to accommodate the fast transients associated with the beam pulse. In a proton accelerator for nuclear fuel breeding or other 100% duty factor applications, this problem disappears and may be replaced by the stringent requirements associated with the transport of a very high power beam. In particular it is estimated[1,2] that a breeder accelerator would require a beam spill of less than 50 GeV.pA/m of the proton beam if the γ-ray dose from induced activity, one hour after shutdown, is to be kept below 2.8 mrad/h (280 mGy/h) at 1 metre from the axis of the machine. In addition to emittance filters, this requirement demands both an accelerator structure which is stable under heavy beam loading and a field control system which will reduce the effect of all disturbances. It is estimated[3] that the accelerating field must be stable to 1% in amplitude and ± 1° in phase.

The Electron Test Accelerator (ETA) at Chalk River[4,5] has been built to study the behaviour of standing wave structures operated with heavy beam loading at 100% duty factor. This paper discusses the design of the accelerating field control systems and describes their behaviour when a graded-β side-coupled, standing wave structure accelerated a bunched 80 keV electron beam of 20 mA to 1.5 MeV.

Field Control in Linear Accelerators

In accelerators with a beam pulse width of a few microseconds, open loop control systems must be used for some parameters whereas closed loop systems can be used to reduce the effect of slow disturbances. The Stanford Two Mile Accelerator uses feedback techniques to optimize beam parameters in succeeding beam pulses[6]. High average current machines with long pulses need a closed-loop control system active during each pulse. The task of accommodating both the fast beam transient as well as the numerous slow disturbances in a high power machine has been tackled successfully by Jameson et al. at Los Alamos[7].

More recently, a new generation of linear accelerator structures used in storage rings has brought its own special problems. These accelerator structures are powered continuously, hence they have control problems similar to those in 100% duty factor machines. However for maximum luminosity, the accelerated charge is compressed into a few micropulses each of which can take up to 60% of the stored energy in the cavity[8]. This major disturbance cannot be controlled dynamically for each pulse. The beam-driven excitation of the structure is a property of the structure and the bunch shape.

Although the beam power of a breeder accelerator will be over two orders of magnitude greater than that in a storage ring, recent developments and experience with rf control systems for rings will make significant contributions to the design of rf systems for such a 100% duty factor linear accelerator[9]. In particular, the rf power sources for a breeder accelerator are likely to be klystrons and structures operated at high mean power are common to both systems. In contrast to the storage ring it is expected that the micropulses in a linear accelerator will be equally filled. This assumption is justified in the absence of contrary experimental evidence, hence the major external disturbances will originate from thermal and relatively slow electrical disturbances. Both rf systems require regulation of structure resonance, field amplitude and phase, hence their control problems are similar.

In spite of the inherent coupling by common elements in the system the three control loops for ETA have been designed so that each variable is controlled independently. Lee[10], using an equivalent circuit model, has derived optimum values for the system parameters and calculated the requirements for steady-state beam loading compensation. To compensate for reactive beam loading one can either detune the cavity or change the phase of the rf power source. The former method is used at SPEAR where a tuner in each individual cavity is used not only to compensate for thermal effects but also to compensate for reactive beam loading. Thus their "transmitted phase" is always fixed. We have used the latter approach with the amplitude and phase of the accelerating field as directly controlled variables. Control loops monitor the field in the structure, compare its amplitude and phase with set points and the resultant error signals change the drive signal to the klystron. A separate tuner and temperature control system keeps the structure always in tune at minimum reverse power.

ETA Field Control

Resonance Control

Before turning-on the beam, all rf structures in a multi-tank accelerator must be resonant at the same frequency and excited from a single master oscillator. The resonant frequency of the graded-β structure in ETA shifts by 380 kHz, 10 times the structure bandwidth, in going from an initial cooling water temperature of 22°C to 35°C at design power of 2.5 kW/cell. The block diagram of the resonance control system in Fig. 1 shows two modes of operation. Initially, each structure determines the frequency of a dedicated "start-up" oscillator. In this way, rf heating can be used to bring the structure to operating temperature, eliminating the need for a separate heating system. This mode is labelled Automatic Frequency Control (AFC). To protect the klystron from excessive reverse power it can only be switched to the master oscillator when the frequency difference between the structure resonance and the master oscillator is less than 1.5 kHz. Using temperature alone to tune the structure, the start-up time to establish the necessary thermal stability is too long. A fast-acting mechanical tuner in a single cell brings the tank to the master oscillator frequency in about 4 min and then the beam can be turned on. It also eliminates the difficult problem of temperature control by water cooling. This mode is labelled Automatic Mechanical Control (AMC) in Fig. 1 and is the accelerator operational mode for ETA. As all beam experiments reported in this paper were done with a single structure, only the AFC mode was used.

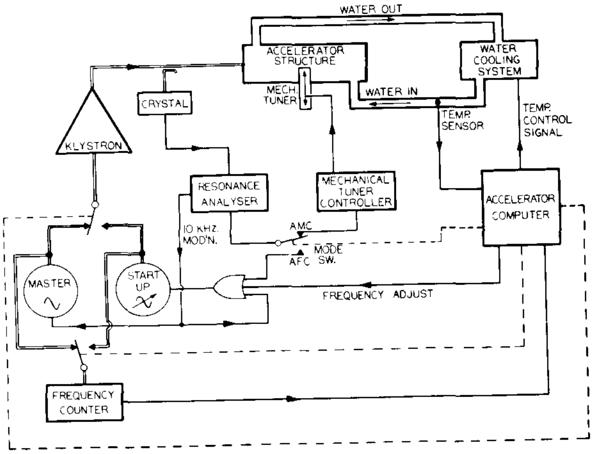

Fig. 1 Resonance control system showing the two modes of operation
(a) Automatic Frequency Control (AFC)
(b) Automatic Mechanical Control (AMC) used for normal acceleration operation.

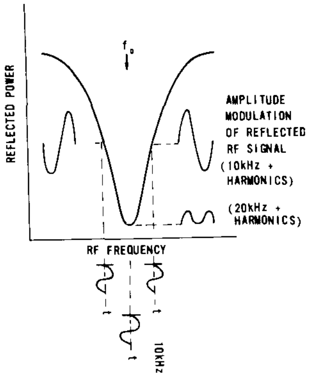

Fig. 2 Resonance analyzer scheme using phase inversion of a demodulated audio signal at rf resonance.

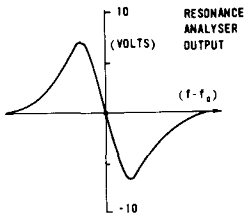

Fig. 3 Analyzer output as a function of frequency.

The method we use for detecting structure resonance was developed at Chalk River by Bayly and Bax[11]. The principle is illustrated in Fig. 2. The oscillator frequency is modulated ± 0.5 kHz at an audio frequency of 10 kHz. Figure 3 shows that the fundamental component of the modulation on the reflected power undergoes a phase inversion from one side of resonance to the other. Phase detection at the modulation frequency by the resonance analyzer (Fig. 1) gives the response shown in Fig. 3. The analyzer has zero output at resonance and at large departures from resonance. To bring the analyzer within operational range an initial frequency search is necessary. Because mistuning is detected as modulation of the rf amplitude at a fixed audio frequency, the output signal is independent of rf phase and therefore insensitive to reactive beam loading. The loop gain is reduced when beam loading broadens the structure resonance but is independent of the reverse power level. Our experiments have shown that a simple proportional controller is adequate for our present purposes and should also be suitable for much higher beam currents. Methods for providing a dynamic match to keep the reverse power level at zero are under study but none of them would influence this approach to resonance control.

Phase Control

Many disturbances affect the rf phase, of which the dominant ones are 360 Hz ripple on the klystron high voltage supply, thermal effects, beam loading and klystron power changes. These require a dynamic range of 65°. An additional 450° is provided to investigate beam-cavity effects. The controller has a roll-off frequency of 1 kHz so that it will not respond to the frequency modulation of the resonance control loop.

The phase control system has been described in detail previously[12]; its principles are shown in

Fig. 4. A dual-channel super-heterodyne receiver mixes the rf signals and retains the phase information at the intermediate frequency of 10 MHz. An error signal proportional to the phase difference between the structure field and a set point derived from the buncher field is produced by a digital phase detector. Digital phase detection was chosen so that the error signal would be independent of field amplitude and the characteristics of detectors[7]. The error signal produces a compensating phase change in the klystron drive line by adjusting the impedance of varactor diodes mounted in an air-dielectric, silver plated coaxial line. Although the variation of insertion loss of the phase shifter is 2 db over its full range, the saturated amplifier in the drive line prevents this change in level coupling into the amplitude loop.

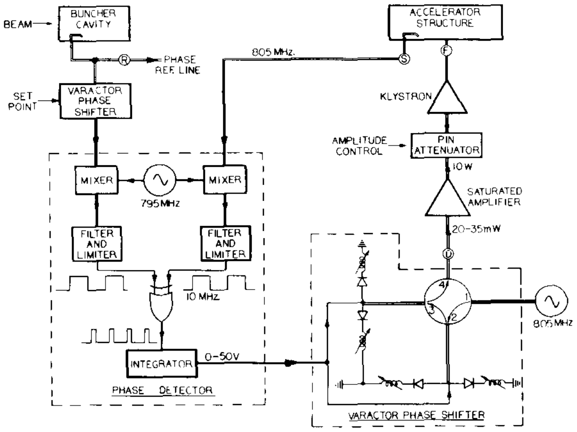

Fig. 4 Block diagram of phase control system.

Amplitude Control

All work on stabilizing the field level in the structure has been done with the klystron unsaturated. It is recognized that a saturated klystron with a controlled high voltage supply or modulating anode would be necessary for maximum efficiency. An unsaturated klystron could however be tolerated during unusual conditions where, for example, fast response is necessary or during run-up of a heavily beam-loaded system.

The system used for the present experiments is shown in Fig. 5. A Schottky hot carrier diode monitors the field level in the structure A. Its output B is compared with the set-power level C to produce a signal D which is amplified to produce the control signal E for the PIN attenuator. The rf drive to the klystron input cavity F gives the required output G from the klystron. All elements, except the Schottky diode and its amplifier, are elements in the forward part of the control loop and hence associated disturbances are regulated. The diode amplifier circuit is used to produce a unipolar signal from the bipolar detector signal and the unipolar set-power level.

At each of the labelled points in Fig. 5 the signal is shown as a function of set-power level illustrating the behaviour of the loop under actual accelerator operating conditions. The loop will function over a power range of about two decades. The need for this requirement will be seen in the next section. The gain of the loop is a strong function of the output power versus drive power characteristic. The curves of Fig. 5 were taken with the klystron high voltage set to give klystron saturation at 75 kW (at which power the loop gain is zero).

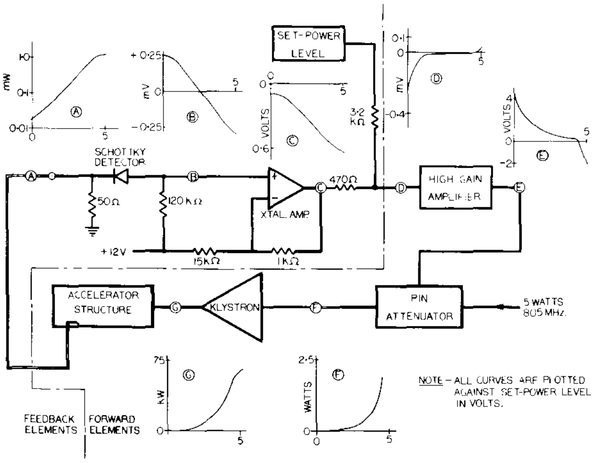

Fig. 5 Schematic diagram of amplitude controller and behaviour at test points in the closed system as the set-power level is changed.

Operation of Control System

The accelerator start-up procedure is as follows. The amplitude loop is closed at a set-power level which delivers about 1 kW to the structure. The computer searches to find resonance by adjusting the frequency of the start-up oscillator until the structure field is maximized and the resonance loop locks. (Only at this power level is the klystron tolerant to the high voltage standing wave which usually results during the frequency adjustment.) The structure power is then increased in a few milliseconds to the operating level of 32 kW by changing the set-power level. When the structure frequency reaches the master oscillator frequency the drive source is transferred to the master. The phase control loop is locked and the required phase set-point selected. The electron gun is turned on; a current of 20 mA can be reached within a few seconds.

Experiments have been done at various structure power levels and over the full range of relative phase between the buncher and graded-β structure. All beam experiments to be described were done in AFC mode hence both structure and buncher were excited by the start-up oscillator only. The tuner, therefore, was not the compensating element in the resonance control loop. At a constant current of 10 mA the tuner was moved so that the frequency shifted by 100 kHz. There was a small change in beam transmission but more instrumentation is required before the behaviour of the beam, particularly in the E-ϕ plane, can be investigated.

The performance of the amplitude control system is summarized in Fig. 6. After a preliminary run up to adjust the beam transport for maximum transmission the beam current was increased from zero to 15 mA and then reduced to zero over an 18 minute period. The upper curve in the figure shows that the forward power increases smoothly with an increase in beam current. The small departure from linearity is caused by the change in the match. The lower curve shows the variation in field amplitude at the controlled point in the structure. The data points are plotted as percentage deviation from that at zero beam and the rms deviation is less than 0.3% over the current range.

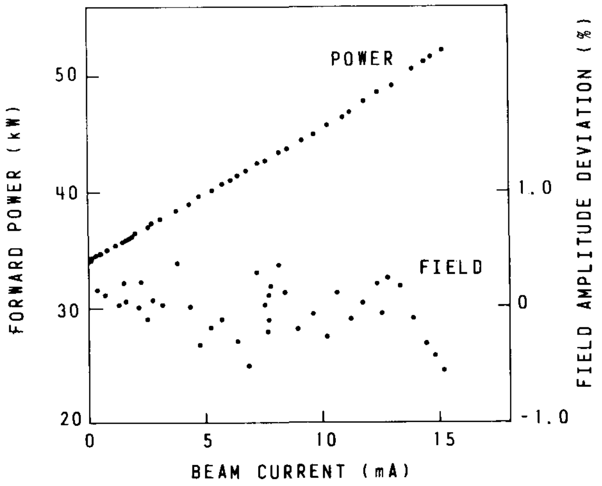

Fig. 6 The variation in beam power and the percentage change in field amplitude as a function of beam power.

Phase control performance is illustrated in Fig. 7. As in the amplitude measurements the beam transport was adjusted for maximum beam transmission at 16 mA. The beam current was varied and the corresponding variation of the phase was recorded at various points. Curve (a) shows the variation in beam current and curve (b) shows the effect of reactive beam loading on the phase difference between the structure field and a forward power directional coupler in the waveguide feed to the structure. Fraser et al.[5] discuss the observed structure lag of 4°. Curve (c) is the time variation of the phase shift across the klystron. A thermal disturbance caused by temperature variation of about 7°C in the klystron water supply is responsible for the cyclic phase variation. This is superimposed on the phase shift caused by the corresponding changes in the required klystron output. Curve (d) shows the phase shift required by the klystron drive to compensate for all disturbances. Curve (e) shows the phase of the accelerating field relative to the buncher cavity. Although the superposition of all these disturbances could result in a phase change of 21°, the phase was held constant with respect to the buncher within 1°.

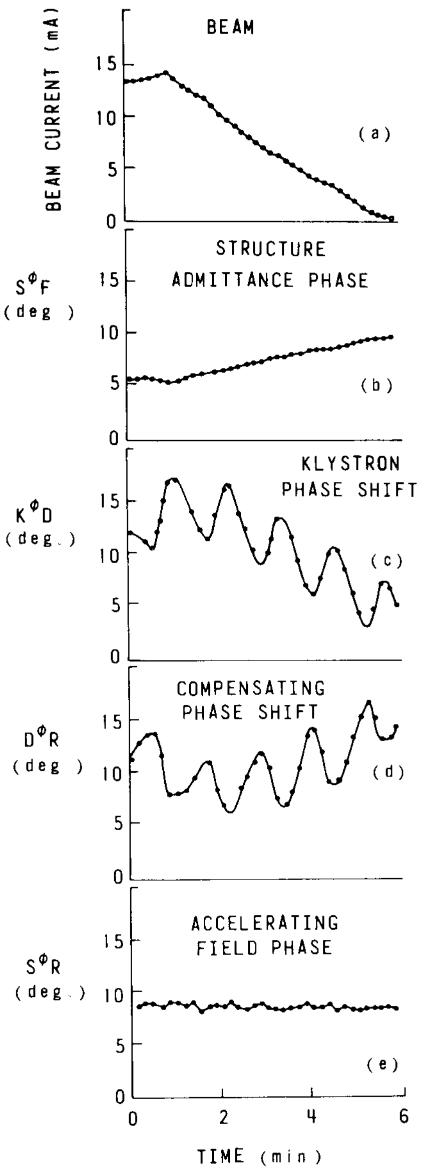

Fig. 7 Time variation of beam-created phase changes measured between different points in the rf system. The points are designated by alphabetic characters in Fig. 4, for example, $S^{\phi}F$ means the phase shift between points S and F.

Conclusions

A stable control system has been developed for a side-coupled standing-wave structure operated at 100% duty factor. It is relatively simple and economical, and up to 50% beam loading, it controls the amplitude and phase of the accelerating field to within 0.3% and 1° respectively. The bandwidth of the system is limited to 1 kHz in the present design; we have seen as yet no evidence that this is inadequate. The amplitude control must be supplemented by other methods for most efficient operation of the klystron rf power supplies. Further experiments are planned to study the structure behaviour at higher beam loading and determine the necessary control requirements of a high power proton linear accelerator.

References

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DISCUSSION

D.A. Swenson, LASL: What kind of device are you using to create the phase shift within the rf drive?

McKeown: The phase shifter is a Varactor phase type phase shifter; it's a four port circulator with a voltage control Varactor and a tuned coaxial line. It has a range of about 400°.