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AN IMPROVED PHASE-CONTROL SYSTEM FOR SUPERCONDUCTING LOW-VELOCITY ACCELERATING STRUCTURES

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Summary

Microphonic fluctuations in the RF eigenfrequency of superconducting (SC) slow-wave structures must be compensated by a fast-tuning system in order to control the RF phase. The tuning system must handle a reactive power proportional to the product of the tuning range and the RF energy content of the resonant cavity. The accelerating field level of many of the SC cavities forming the ATLAS linac has been limited by the RF power capacity of the presently used PIN-diode based fast-tuner. A new system has been developed, utilizing PIN diodes operating immersed in liquid nitrogen, with the diodes controlled by a high-voltage VMOS FET driver. The system has operated at reactive power levels above 20 KVA, a factor of four increase over an earlier design.

Introduction

In general, ambient acoustic noise will excite mechanical vibrational modes of resonant cavities which then cause fluctuations in the RF eigenfrequency. In normal-conducting accelerating structures, such fluctuations are typically much smaller than the intrinsic resonator bandwidth and do not appreciably effect the RF phase.

The case is different for superconducting resonant cavities for the acceleration of heavy-ions. Such structures exhibit Q's of a few times 10^9, corresponding to an intrinsic bandwidth of a few hundredths of a hertz. In the environment of an operating accelerator, it is difficult to reduce microphonic induced variations in resonator RF eigenfrequency below a few tens of hertz peak-to-peak.

For the ATLAS linac, beam currents are typically a few particle nanoamperes and do not appreciably load even superconducting resonant cavities. Thus, even when coupled to the driving RF amplifiers, the effective resonator bandwidth is smaller than the microphonic-induced eigenfrequency jitter. Under these circumstances, a fast-tuning system is required to cancel the effects of mechanical vibration and enable control of the RF phase.

Basic Elements of the Fast-Tuner

The fast-tuning system for ATLAS is based on PIN diodes used to switch the superconducting resonator between two frequency states chosen to bracket the reference clock frequency [1,2,3,4]. In the high-frequency state, the resonator RF phase precesses forward relative to the clock, and in the low frequency state, backward.

Phase control is achieved with a diode driver which switches the diodes between the two states at a rate of 25 KHz. Within the switching period, the diodes can be turned on for a controlled time which can be varied from 5% to 95% of the switching cycle. Modulation of the duty factor provides an effectively continuous control of the direction of phase precession, hence also the mean RF phase.

The principle microphonic-excited vibrational modes are below 150 Hz in frequency, so that the discrete phase correction steps, occuring at the much faster rate of 25 KHz, are in effect continuous. The finite-step effects introduce a phase noise of typically one degree peak-to-peak, well within acceptable limits.

The PIN diode must switch a reactive power P = I(on-state) x V(off-state) which is proportional to the product of the tuning range and the RF energy contained in the superconducting resonator, given by

$$P = 8\pi\, \Delta f\, E_a^2 U_0$$

where Δf is the tuning range, E_a the accelerating field level and U_0 the RF energy content at $E_a = 1$ MV/m, typically 150 mJ. (This result is a consequence of the Boltzmann-Ehrenfest theorem, and is independent of the particular coupling scheme used.)

The reactive power load is typically 5 kVAR or more, and to operate the tuner at room temperature would require bringing a high-power RF line out of the linac cryostat for each of the many resonant cavities. For ATLAS a fast-tuner was developed which operates at 77 K, and is directly attached through a half-inch long, thin-wall stainless steel tube to the 4 K superconducting resonators.

The previous version [5] of this device was coupled capacitively to the superconducting resonator through a 77 K copper probe inserted through a port on the SC cavity. RF currents in the copper probe caused 10-20 watts of joule heating, which was cooled by conduction through a beryllium-oxide ceramic, joined by brazing to the copper probe tip.

In the course of a decade of operation, involving re-cycling to room temperature typically several dozen times, the thermal properties of many of the ceramic to metal braze joints degraded, requiring operation at reduced field levels to prevent thermal runaway of the capacitive probes.

Upgraded System

Development of a new system focused on improving thermal stability and upgrading the diode driver to improve reliability and RF power capability.

Figure 1 shows a cross-section of the new fast tuner which utilizes an inductive coupling loop formed from a 25 x 6mm copper bar, both ends of which are cooled by direct metallic heat conduction to liquid nitrogen. While this avoids cooling by conduction through a ceramic, the cost is requiring a high-RF-voltage, high-vacuum, 77-K feedthrough. This was successfully formed by sandwiching a ring of high-density alumina ceramic between two metal flanges with indium O-ring seals.

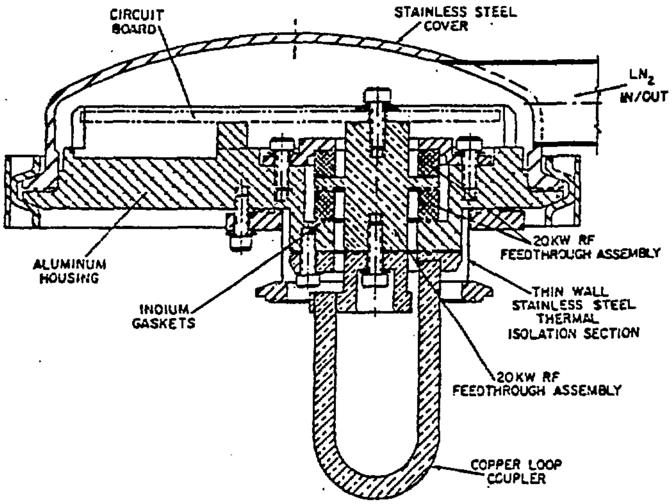

Fig. 1 Cross-section of the housing for the PIN-diode based fast-tuner, which directly mounts to a superconducting resonator at 4.6 K. The housing is filled with flowing liquid nitrogen.

The internal portion of the fast tuner is filled with flowing liquid nitrogen, so that the pin diodes and associated circuit elements are directly immersed in coolant. The diodes are additionally mounted to a copper heat sink (also immersed in LN_2), with a thin indium gasket insuring good thermal contact.

Figure 2 shows the equivalent circuit of the fast-tuner, which consists of a resonant circuit (loop-coupled to the superconducting resonator) which is switched between two frequency states by the PIN diodes. Several diodes are operated in parallel to provide redundancy, and each diode is fused so that if a diode fails by shorting, it can be removed from the circuit by blowing the fuse with a reverse-bias current of about 30 amperes.

Operating the diodes at 77 K provides an important benefit in that the minority carrier lifetime is reduced by more than a factor of ten from room temperature. This enables the fast switching of much thicker I-region diodes, which have higher RF PIV ratings, and give an increased power handling capability. The diodes used [6] have proven reliable in our application where they are repeatedly cycled from room temperature to 77 K and routinely and continuously switch more than 5 KVA at a switching rate of 25 KHz.

A room-temperature diode driver provides a 700-V reverse bias to turn the diodes off, and 2 to 3 A of forward current to turn them on. Under these conditions, the diodes have been observed to support a peak RF voltage of 700 V and a peak RF current of 33 amperes.

The RF losses in the PIN diodes are small in both the on and off states. The key to keeping overall RF losses small (and diode lifetime long) is to keep the transition time between the two states as short as possible. This requires a substantial pulse of current to remove carriers from the diode junction in turning off, and to supply carriers in turning on.

A VMOS FET based driver has been developed which switches the PIN diodes in approximately 100 nsec. The driver must produce a 700 V pulse and peak currents in excess of 20 A during the 100 nsec transition time. To meet these goals, we used high power n-channel enhancement-mode FET transistors [7]. A pair of these elements in a simple cascode switch is used for an on switch, and another pair for an off switch. The output is transient protected with a stack of zener diodes. Also, the transmission line carrying the drive pulses to the diodes is terminated with a 50-ohm resistor to damp transients.

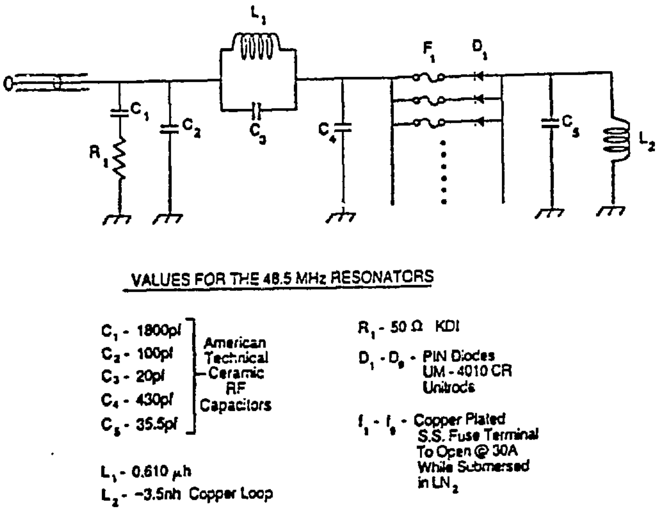

Fig. 2 Schematic for the 77-K portion of the fast-tuning system. The inductance L2 is the coupling loop to the SC resonator (shown in Fig. 1). The other components are mounted on a teflon circuit board immersed in liquid nitrogen. The transmission line brings diode-switching pulses from a room-temperature circuit.

Tests

The upgraded fast-tuning system has been tested off-line with a 97-MHz split-ring of the type used in ATLAS. In these tests, phase-locked operation at accelerating fields in excess of 6 MV/m was achieved, and the system was allowed to run for more than 8 hours. At these field levels the fast tuner was switching more than 20 kVA and dissipated a total of 70 watts into liquid nitrogen. The power loss is composed of two roughly equal terms: RF losses and losses associated with the switching of the PIN diodes.

The recently completed positive ion injector linac for ATLAS incorporates the upgraded design. In initial tests, five of the new fast-tuning units have operated at typically 6 KVA for more than two hundred hours with no serious malfunctions.

Conclusions

An upgraded fast-tuning system has been developed that provides a factor of four increase in reactive-power capability relative to the earlier design. The increased capacity will permit phase stabilization of superconducting resonators at higher field levels. In particular, it has enabled the operation of very-low-velocity superconducting structures at gradients of more than 4MV/m in the ATLAS positive-ion injector linac.

Acknowledgment

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