UPGRADED PHASE CONTROL SYSTEM FOR SUPERCONDUCTING LOW-VELOCITY ACCELERATING STRUCTURES

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Abstract

Microphonic-induced 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 frequency range and the RF energy content of the Rf cavity. The fast tuner for the SC resonators in the ATLAS heavy-ion linac is a voltage-controlled reactance based on an array of PIN diodes operating immersed in liquid nitrogen. This paper discusses recent upgrades to the ATLAS fast tuner which can now provide as much as 30 KVA of reactive tuning capability with a real RF power loss of less than 300 watts. The design was guided by numerical modeling of all elements of the device. Also discussed is the RF coupler which can couple 30 KW from 77 K tuner to a 4.2 K resonant cavity with less than 2 W of RF loss into 4.2 K.

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 nor 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 the circumstances, a fast-tuning system is required to cancel the effects of mechanical vibration and enable to control of the RF phase.

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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 cam 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, occurring 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_{react} given by

$$P_{react} = 8\pi \; \delta f \; U_0 \; E_a^2$$

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. This result is a consequence of the Boltzmann-Ehrenfest theorem, and is independent of the particular tuning scheme used.

The reactive power load is typically 10 KVA 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.

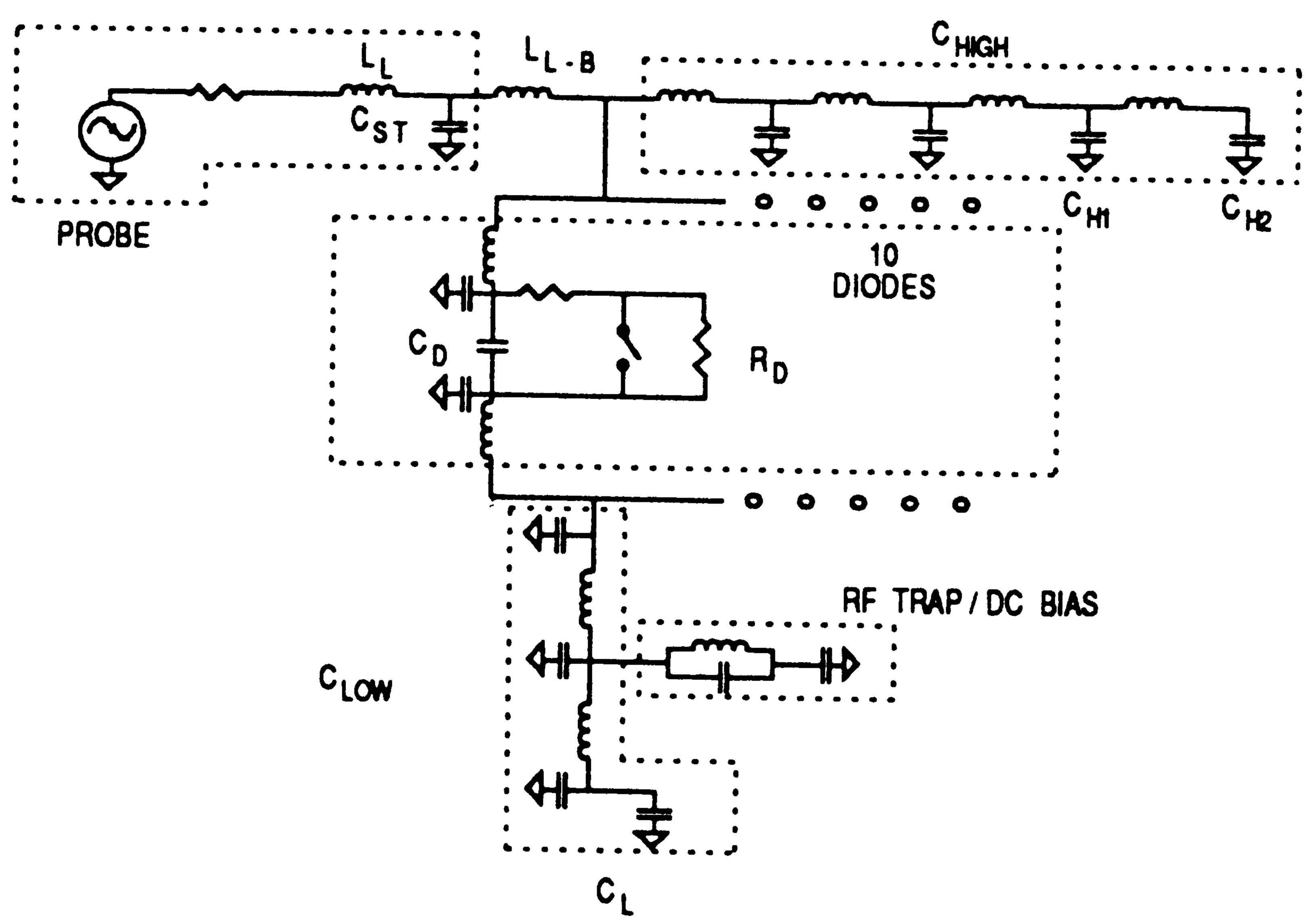

Fig. 1. Equivalent circuit model for the fast-tuner. Components modeling one of ten PIN diodes are shown.

The first 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. The properties of this ceramic to metal braze joints degraded after re-cycling to room temperature several times.

A more recent version [6] of this system was developed to improve thermal stability. In this version, an inductive loop was used to couple the fast tuner to the SC resonator. Both ends of the loop were cooled by direct metallic heat conduction to liquid nitrogen. This cooling was provided by filling the internal portion of the fast tuner with flowing liquid nitrogen. This version of the fast tuner was installed in the two first cryostats of ATLAS and has been operating for the last two years.

Although performance was significantly improved after this upgrade, overall resonator performance did not increase as much as had been hoped for. Also, the very low velocity resonant cavities for the PII linac for the uranium upgrade of ATLAS are less stable mechanically than the ATLAS resonators and require an increased tuning capacity; the performance of PII would still be limited by fast-tuner. For these reasons, further development of the fast-tuner system was undertaken.

Fast-tuner Development

The first step was to numerically model as an ac network all elements of the fast tuner system (using SUPERNOVA code). The model was checked by extensive measurements of the rf currents and voltages at virtually all accessible portions of the tuner. The equivalent circuit that eventually evolved is shown in Fig. 1; this model predicts with typically 5% accuracy the voltages and currents at the various elements of the tuner over the octave bandwidth (48.5 - 97 MHz) required by the various ATLAS resonant cavities.

As a result of this analysis, the high-power circuit board and virtually all circuit elements were substantially modified. For example, the fast-tuner employs 10 high-power PIN diode switches operated in parallel to provide both increased capacity and increased reliability through redundancy. It was found that the rf current through the various diodes differed by as much as a factor of two, the imbalance being corrected by shifts of various conducting paths by typically a few mm.

As the fast-tuner was modified, a number of tests with highly-instrumented superconducting resonators were performed.

In the course of these tests it became clear that excessive rf losses were occurring in the thermal transition between the 77 K tuner and the 4.2 K superconducting cavity (see Fig. 2). Measurements of the rf magnetic field at the thermal transition showed that the field caused by the coupling loop was substantially higher than had been thought. The coupling loop design was changed by compacting the loop and moving it further into the superconducting cavity and away from the high-loss stainless-steel thermal isolation section. In the present design, shown in Fig. 2, rf losses into the thermal isolator have been reduced more than a factor of ten.

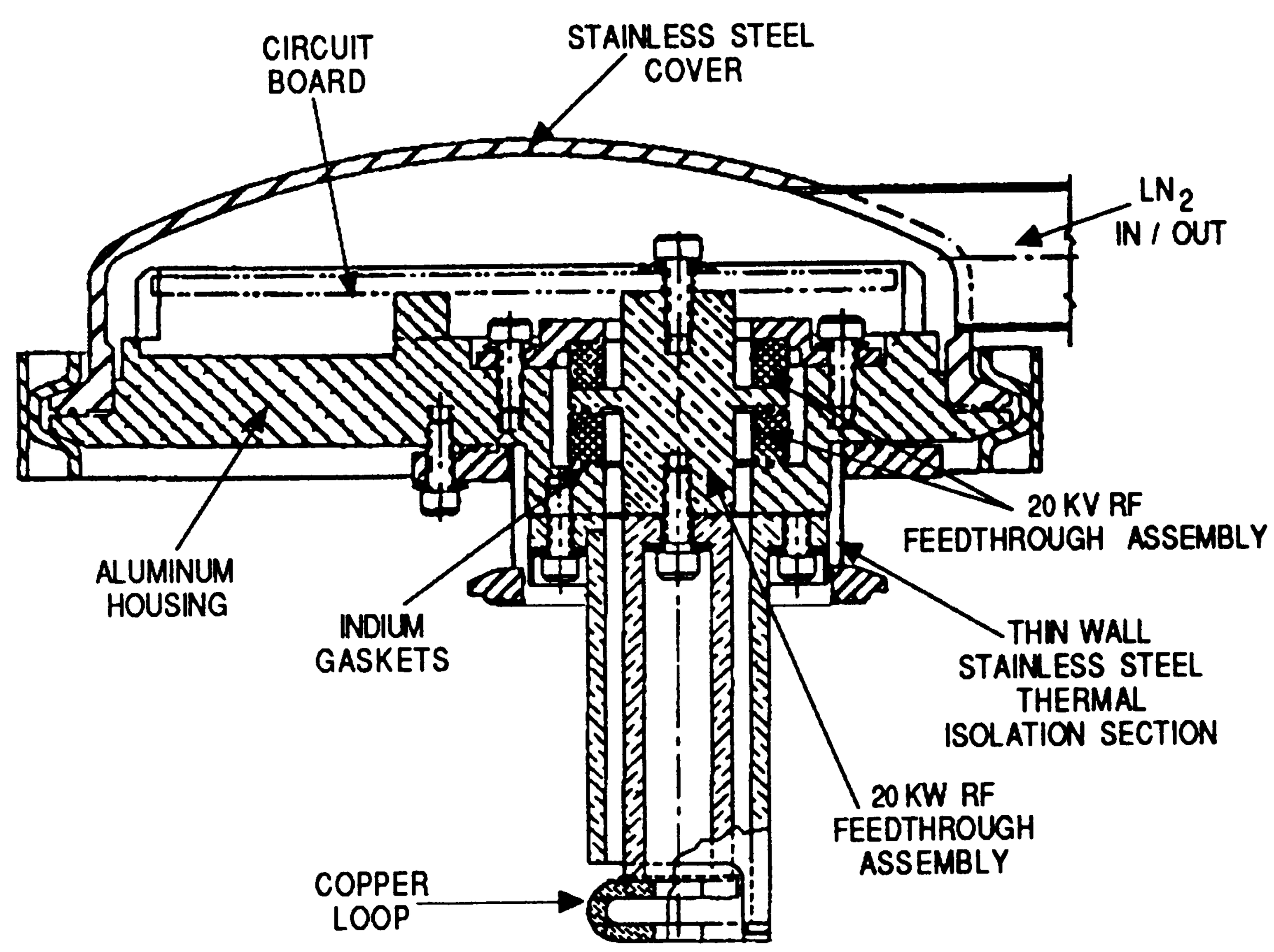

Fig. 2. The fast-tuner unit, which operates at 77 K. The copper loop projects into the superconducting cavity, and can couple as much as 30 KVA of reactive power into the tuner. The overall diameter is approximately six inches.

Results and Conclusions

An off-line test of the new fast-tuner design was performed using an I-4 class interdigital resonator, which operates at 72.75 MHz. In this test, the fast-tuner was coupled to provide a 900 Hz tuning window, substantially larger than is used on-line, in order to provide a stringent test of the new design. The tuner was able to control the rf phase of the resonator at accelerating field levels of more than 3 MV/m. At this field level, the fast-tuning system was switching more than 30 KVA of reactive rf power, with a total rf loss of less than 300 watts. The loss into the thermal isolation section and into the 4.7 K resonator was monitored thermometrically, and was found to be less than 2 watts.

The new design provides at least 50% more tuning capacity than the previous version. Also, the relatively more accurate numerical model for the tuner has enabled more reproducible and reliable set-up of the component values for the seven different types of resonant cavities employed in ATLAS.

At this writing, some 30 of the 63 resonant cavities in ATLAS have been fitted with the new design. The results have been both improved operational stability due to increased fast-tuning windows and also higher (typically 10%) operating gradients because of reduced rf loss into the resonant cavities.

Acknowledgements

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References

1. G. J. Dick and K. W. Shepard, Proceedings of the 1972 Applied Superconductivity Conference (IEEE), p649 (1972).

2. D. Schulze, A. Brandelik, R. Hietschold, A. Hornung, F. Spielbock, and L.K. Szecsi Proceedings of the 1972 Proton Linear Accelerator Conference (Los Alamos), p176 (1972).

3. O.D. Despe, K.W. Johnson, and T.K. Khoe IEEE Trans. Nucl. Sci. NS-20, p71 (1973).

4. G. Hochschild, D. Schulze and F. Spielbock IEEE Trans. Nucl. Sci. NS-20, p116 (1973).

5. ATLAS - A Proposal for a Precision Heavy Ion Accelerator, Physics Division, Argonne National Laboratory (1978)

6. J.M. Bogaty, B.E. Clifft, K.W. Shepard and G.P. Zinkann, Proceedings of the 1989 IEEE Particle Accelerator Conference, March 20-23, Chicago, Illinois, p1978 (1989).