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

$$P = 8\pi \; \Delta f \; E_a^2 U_o$$

where Δf is the tuning range, E_a the accelerating
field level and U_o 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.
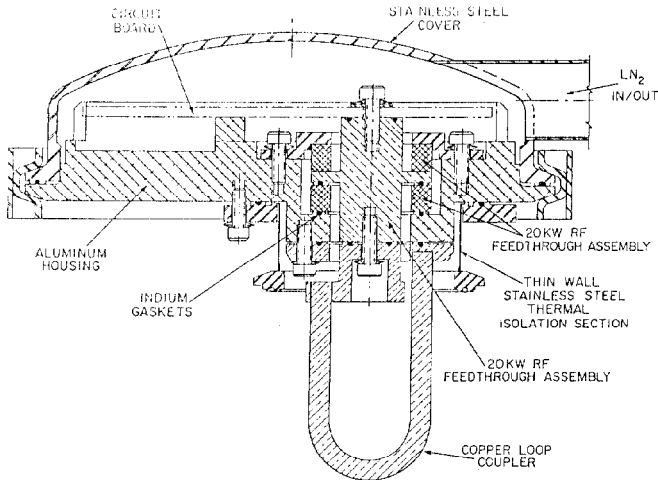

Fig. 1   Cross-section of the housing for the
         PIN-diode based fast-tuner, which
         directly mounts to a superconducting
         resonator at 4.6 K. The housing
         is filled with flowing liquid nitrogen.

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.
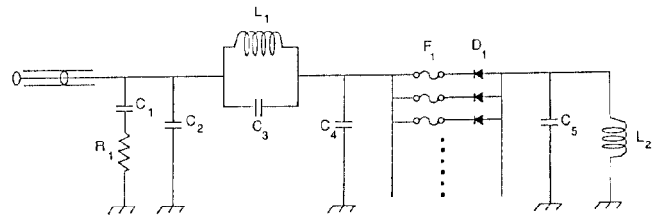
VALUES FOR THE 48.5 MHz RESONATORS

C_1 - 1800pf ⎤
C_2 - 100pf   ⎥ American
C_3 - 20pf   ⎥ Technical
C_4 - 430pf   ⎥ — Ceramic
C_5 - 35.5pf ⎦   RF
                  Capacitors

L_1 - 0.610 μh
L_2 - ~3.5nh Copper Loop

R_1 - 50 Ω KDI

D_1 - D_9 - PIN Diodes
              UM. - 4010 CR
              Unitrode

f_1 - f_9 - Copper Plated
              S.S. Fuse Terminal
              To Open @ 30A
              While Submersed
              in LN_2

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 trans-
         mission 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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3. O. D. Despe, K. W. Johnson, and T. K. Khoe, IEEE Trans. Nucl. Sci. NS-20, p 71 (1973).
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5. ATLAS - A Proposal for a Precision Heavy-ion Accelerator, Physics Division, Argonne National Laboratory (1978).
6. Unitrode type UM4010CR.
7. IRF H50 VMOS HEXFET