# PROPOSED MICROWAVE SYSTEMS FOR SUPERCONDUCTING RADIOFREQUENCY BEAM SEPARATORS*

H. J. Halama and H. Hahn
Brookhaven National Laboratory
Upton, New York

## Summary

In this paper various aspects of the microwave system for RF beam separators using superconducting iris-loaded deflectors are discussed. This microwave system differs significantly from a conventional design. The differences stem mainly from the very high Q, the mandatory standing wave operation, and the lack of frequency adjustments by temperature changes. Successful operation of the separator depends on keeping two narrow bandwidth resonators ($\Delta f \approx 20$ Hz) at the same frequency, $f_0 \approx 1.3$ GHz, and in rigid phase relationship. Mechanical tuning of the deflectors must be provided in the form of a variable path length for a resonant ring or in the form of an adjustable short for a resonant cavity. The resonant deflector can be powered either from a common source or by using the deflector as frequency determining element in an oscillatory system. Both microwave systems are described and their relative merits are compared.

## I. Introduction

A design study of an RF beam separator intended for counter experiments in the momentum range from 4.5 to 19 GeV/c was carried out.[1] It was shown that the required pulse length of several 100 ms can only be achieved by use of superconducting deflectors. The separation scheme is based on a Panofsky type separator consisting of two short RF deflectors separated by a drift space. The principal parameters of this device were established by optimizing the transmission of wanted particles. The operating wavelength was found to be about $\lambda_{opt} = 24$ cm, whence follows the drift space L = 33 m. A deflector length of $\ell = 3$ m was considered adequate. The scheme adopted is similar to the RF beam separator now in operation at Brookhaven,[2,3] and at CERN,[4] and the design requirements are comparable in many respects. The use of superconducting deflectors, however, results in differences, some of which are of major importance, and new technical solutions are required.

In superconducting structures it is, in principle, possible to obtain deflecting fields which are comparable to those in conventional deflectors. The RF power is, however, considerably reduced. The reduction is conveniently expressed by aid of the improvement factor, I, and values in the order of $I = 10^5$ are expected. The RF power levels required are therefore readily obtained from commercial tubes, even if CW operation is intended. The pulse length of several 100 ms corresponds for all practical purposes to CW operation. Measurement of phase and amplitude is possible and detected errors must be corrected during the pulse by feedback loops. In fact, pulsed operation with a duty factor of 0.3 is only recommended to simplify the refrigeration problems, whereas the design of the microwave system will be based on CW operation.

The small losses in superconducting structures are best utilized in standing wave operation, which converts the deflector into an extremely narrow band device. This will impose stringent requirements on the frequency and phase stability of the RF source. In conventional structures the temperature is used to equalize the operating frequency of both deflectors. In superconducting devices this freedom no longer exists and very tight tolerances are necessary. Despite the most careful machining it will be impossible to bring both deflectors to the same frequency and some means for tuning must be provided. For the same reason it seems desirable to make the RF source variable in frequency. Moreover the deflector should be designed to be insensitive to mechanical errors by selecting the highest absolute value of group velocity. This provides the additional benefit of larger spacing of neighboring resonances.

In this paper the problems encountered with the microwave system for a superconducting RF beam separator are discussed and possible solutions are suggested. Considerations on the same subject, which led to somewhat different conclusions, were presented previously as an internal report.[5] Although extensive studies on the fabrication of superconducting structures were initiated recently at this laboratory, a discussion on this subject is postponed until more conclusive results will be available. Results published by groups at Stanford,[6] Paris,[7] and Karlsruhe[8] seem to justify our assumption that improvement factors, as required for the economical application of superconductivity, can be achieved with lead-coated copper structures.

## II. General Considerations

The operating frequency should be close to the theoretical optimum, but the actual choice must consider the availability of microwave equipment. It is fortunate that the theoretical value falls into the phased-array radar band, and microwave components are commercially available. We therefore suggest to use $\lambda_0 = 9.0$ in. $\hat{=}$ 22.86 cm, which corresponds to $f_0 \approx 1.311$ GHz.

As mentioned in the introduction, standing wave operation in the form of resonant cavities (RC) or resonant rings (RR) is necessary. Both configurations exhibit a finite bandwidth $\Delta f$ given by

$$\Delta f = f/Q \tag{1}$$

where Q represents the loaded quality factor. At critical coupling (which makes full use of the RF power delivered by the source) the quality factor is known to be $Q = \frac{1}{2} Q_0$. The unloaded $Q_0$ of

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deflectors, at normal temperatures and at the operating frequency chosen, follows from well known scaling laws to be $Q_o(Cu, 273^o) \approx 15000$. To estimate the Q of superconducting devices, it is necessary to know the improvement factor I. The theoretical I can be determined from the formulas given by Khalatnikov et al.[9] Operation at $2^oK$ is anticipated, where the theoretical $I = 1.8 \times 10^6$. Improvement factors achievable in large structures of complicated shape are expected to be much smaller and it is assumed that $I \approx 10^5$ can be obtained. It follows that $Q \approx 7.5 \times 10^8$ and the bandwidth $\Delta f \approx 2$ Hz at critical coupling.

This extremely narrow bandwidth will impose demanding requirements on the stability of the signal source and the required temperature stability. Overcoupling will reduce this problem but this approach can only be taken if excess RF power is available. The power dissipated in the deflector, P, is related to the power delivered by the source, $P_s$, according to[10,11]

$$P_s = \frac{(\nu + 1)^2}{4\nu} P \tag{2}$$

with $\nu = \kappa/\kappa_{cr}$, where $\kappa$ is the coupling coefficient and the critical coupling is given by $\kappa_{cr} = 1$ for RC and $\kappa_{cr} = (2\alpha\ell)^{\frac{1}{2}}$ for RR. The loaded quality factor of overcoupled structures is

$$Q = \frac{Q_o}{1 + \nu} \quad . \tag{3}$$

It appears desirable to operate at least with $\nu \approx 20$, whence follows the bandwidth of $\Delta f \approx 20$ Hz. In this context it should be pointed out that the RF power not dissipated in the deflector is reflected in a RC, whereas in a RR it is dumped into a load. The input of a RR always looks terminated.

The power requirements for each deflector can be established if a 3 m long superconducting structure with a typical shunt impedance of $R \approx 10^6$ MΩ/m is assumed. The case of a resonant ring is treated first. The maximum equivalent deflecting field is limited by the critical magnetic field of the superconductor and by field emission to values $E_o \leq 7$ MV/m. The power dissipated in the deflector is given by

$$P = \frac{E_o^2 \ell}{R} \quad \text{for RR} \tag{4}$$

which follows directly from the definition of shunt impedance. Inserting the values mentioned, we obtain P = 150 W. The power required from the source is, on the other hand, $P_s \approx 750$ W based on an overcoupling of $\nu = 20$. The case of a resonant cavity of identical length is slightly different, since the power dissipated at equal $E_o$ is twice that of a RR:

$$P = 2 \frac{E_o^2 \ell}{R} \quad \text{for RC} \quad . \tag{5}$$

Yet, because the permissible deflecting field is only half of that in a RR, it follows that the dissipated power in a resonant cavity is P = 75 W and the power required from the source is $P_s \approx 375$ W. It is seen that for a given source power the overcoupling (and the bandwidth) of a RC can be made twice that of a RR. The design of a RC would be easier, but it must be remembered that the deflection is also reduced.

It is instructive to discuss the effects of an increased improvement factor on the bandwidth and source requirements. For a strongly overcoupled resonator the following approximations are valid:

$$\left.\begin{array}{l} \Delta f \propto \nu/I \\ P_s \propto \nu/I \end{array}\right\} \text{ for } \nu \gg 1 \quad . \tag{6}$$

It may be inferred that the maximum bandwidth depends only on the available source power, that is, $\Delta f \propto P_s$, independently of the improvement factor. In conclusion, it appears that a commercial 1 kW CW amplifier klystron is a suitable choice.

The successful separation of particles depends on exact cancellation of unwanted (U) particles. Errors in the microwave system will cause a residual deflection of U particles, $\Delta\theta_U$, which is, in first approximation, given by

$$\Delta\theta_U^2 = (\theta\ \Delta\tau)^2 + (\Delta\theta_1 - \Delta\theta_2)^2 \tag{7}$$

where $\theta$ = peak deflection in one deflector, $\Delta\tau$ = phase error between deflectors, and $\Delta\theta_1$, $\Delta\theta_2$ = errors in deflection in first and second deflector. Some residual deflections can be tolerated if one widens the beam stopper, but this will give rise to an extra loss of wanted particles. A residual deflection of U particles of $\Delta\theta_U/\theta \approx 0.03$ rms is considered acceptable. This limit leads to $\Delta\tau \leq 0.02 \mathrel{\hat{=}} 1^o$ rms and $(\Delta\theta_1 - \Delta\theta_2)/\theta \leq 2\%$. The amplitude stability required should be achieved without great difficulty, whereas the phase stability will demand a carefully designed phase lock system.

## III. Possible Microwave Systems

The choice of the microwave system will depend on the availability of an RF source with adequate stability, that is, better than $10^{-9}$. In a previous report,[5] it was assumed that an RF source with the characteristics desired would not be economical. Consequently, a microwave system was proposed which would use one deflector as the frequency determining element in an oscillating loop consisting essentially of amplifier, variable phase shifter, and deflector cavity. The second deflector cavity is inserted into a similar oscillating loop, which in turn is synchronized in frequency and phase to the first deflector. Although this system promises to be very economical, it is feared that the adjustments of the various servo loops will be somewhat difficult.

It now seems that a phase-locked klystron (for example Raytheon, RK5981) could be employed in a setup similar to the source presently used.[3] The fixed RF reference is derived from a spectrally pure quartz oscillator with long and short term fluctuations of $< 10^{-9}$, whereas the variable IF frequency uses a frequency synthesizer with correspondingly reduced stability. Another approach consists in using a superconducting cavity as the frequency determining element in an oscillating loop. A stable yet variable RF source can be obtained with the arrangement shown in Fig. 1. The power output from either signal source is in the milliwatt range and further amplification by a traveling wave tube must be provided.

A microwave system resembling the conventional solution[3] which is based on an RF source of adequate stability is shown schematically in Fig. 2. The common source signal is split in the hybrid $H_1$ and transmitted via phase stable cables to each klystron amplifier, $A_5$ (for example, Eimac X3002A). The output of 1 kW or so is fed to the superconducting cavity. A fraction of this signal is modulated at 1 kHz in the microwave switch S and returned on the phase stable cable to the Control Station. The phase difference between the signals returned from both Deflector Stations is measured by means of a 3 dB hybrid, $H_2$ . A synchronous detector, $D_2$ , produces the error signal which in turn actuates the phase shifter $P_2$ , thus correcting any error between the deflectors. It is easily verified that one measures the relative phase difference directly between the inputs to the deflectors independently of the cable length. The phase changes occurring between the circulators $C_1$ and $C_2$ are fully compensated as these circuits carry both the correction and the incident signals. On the other hand, the phase drift occurring in elements through which the signal travels but once are halved only. Due to the modulation method and the synchronous detection used, the phase servo is not susceptible to spurious reflections and can work with very poor signal-to-noise ratios. Furthermore, the total loop gain is obtained in an ac coupled amplifier, thus eliminating dc drift which would otherwise correspond to phase errors.

## IV. Deflector Stage

Standing wave operation of superconducting deflectors can be achieved by transforming a conventional waveguide section, i.e., with matched input and output couplers, into a resonant cavity by placing shorts at each end or by inserting the waveguide section into a resonant ring. A resonant ring would be preferable to a resonant cavity because of its larger deflecting fields and smaller RF losses, but the construction of a resonant ring is considerably more complicated and it is anticipated that a resonant cavity will be chosen as a first step.

It is practically impossible to machine superconducting cavities so that their resonant frequency differs less than their bandwidth, and some means for frequency tuning must be provided. Three possible solutions are sketched in Fig. 3: (a) The whole resonant ring containing lead-plated stainless-steel bellows is enclosed in liquid helium and the frequency is affected by adjusting its electrical length. To accomplish this the bellows are stretched or compressed by means of a plunger brought out of the dewar. (b) An alternate method employs a variable phase shifter outside the helium bath. Its room temperature version is discussed in Ref. 12. (c) The third system operates as a SW cavity.[5] Here the output port is terminated with a variable short, S, which changes the phase of the reflected wave and brings the deflector to the desired frequency.

Since both deflectors are driven from the same source, they must be tuned to the same frequency. A deviation from that frequency comparable to the bandwidth must be sensed and immediately corrected. In Fig. 3, a possible provision to detect the resulting phase changes between points, which are electrically furthest apart, is shown. The error signal obtained can be used by a mechanical servo to compensate the errors. Pneumatic tuning, as suggested by Hanson et al., is an attractive possibility.[13]

After the initial adjustment of the deflector, the principal cause for frequency changes will be temperature variations. The change of the surface reactance with temperature entails a frequency shift, $\Delta f_o$ , according to

$$\frac{\Delta f_o}{\Delta T} \approx - \frac{1}{2} \frac{r_\infty f_o}{A} \frac{\Delta(X/r_\infty)}{\Delta T} \qquad (8)$$

where $r_\infty$ is the surface resistance of normal metals in the extreme anomalous region, A is a geometrical constant typical for a structure, and $\Delta(X/r_\infty)/\Delta T$ must be found from theory.[9] It may be computed that $r_\infty = 1.65\ m\Omega$ and A takes values[14] from 140 to 200 Ω, whence $\frac{1}{2} r_\infty f_o/A \approx 6$ kHz. The resulting frequency shift per $1^oK$ versus operating temperature is depicted in Fig. 4. It is seen that a temperature regulation of ± $0.1^oK$ rms causes frequency shifts of $\Delta f = \pm 12$ Hz rms at $4.2^oK$ and of ± 0.8 Hz rms at $2^oK$. Operation at or below $2^oK$ is recommended to avoid undesirable frequency shifts and to provide the improvement factors required. Moreover, this is below the lambda point at which liquid helium becomes superfluid, and heat transport problems are alleviated. The frequency shift due to thermal expansion of copper is $\Delta f/\Delta T \approx (T/^oK)^3 \times 0.05\ Hz/^oK$ and one is justified in neglecting it.

By means of the tuning mechanisms described equality of the resonant frequencies in both deflectors can always be enforced. But deflection of particles demands also synchronism with the deflecting wave, which must be obtained by correct mechanical dimensions. Errors in the outer radius, b, of the iris-loaded deflector cause the largest perturbation of the phase velocity, and our considerations will be limited to this case. The phase slip, $\varphi$ , of an extreme relativistic particle with respect to the wave in the guide is, in first approximation, expressed by

$$\varphi \sim k\ell \frac{c}{v_g} \frac{\Delta b}{b} \qquad (9)$$

where $k = 2\pi/\lambda_o$ , $\ell$ = deflector length, and $v_g$ = group velocity. It is seen that large $|v_g|$ reduce the requirements on the tolerances, and the design study[1] showed that values of about $v_g/c \approx -0.04$ are possible. The deflection in the presence of the phase shift $\varphi$ is reduced to

$$\frac{\sin \frac{1}{2}\varphi}{\frac{1}{2}\varphi} \approx 1 - \frac{1}{24}\varphi^2 \quad . \qquad (10)$$

A permissible drop by 1% establishes the limit $\varphi \leq 0.5$. The mechanical tolerances required by this condition become $\Delta b/b \leq 2.5 \times 10^{-4}$, or in absolute value $\Delta b \leq \pm 50\ \mu m$. To achieve this it may become necessary to dimple the waveguide, which is a method commonly used in electron linacs.

## V. Pulsed Operation

Pulsed operation of the deflectors is possible if its time constant $\tau = Q/\omega_o$ is short compared to the desired pulse length of several 100 ms. As discussed earlier, the quality factor was reduced by overcoupling to about $Q \approx 7.2 \times 10^7$, whence the time constant $\tau \approx 10$ ms. It is seen that the filling of the deflector cavity takes only a small fraction of the operating pulse length and no complications due to pulsed operation are expected. Furthermore, a closer investigation of the microwave system with central source reveals that it would remain operational under pulsed operation.

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Table I. Theoretical properties of superconducting lead at 1.3 GHz.

| T(°K) | I | $\Delta(X/r_\infty)/\Delta T$ |
|---|---|---|
| 1.6 | $1.07 \times 10^7$ | $6.01 \times 10^{-4}$ |
| 1.8 | $3.98 \times 10^6$ | $9.13 \times 10^{-4}$ |
| 2.0 | $1.81 \times 10^6$ | $1.34 \times 10^{-3}$ |
| 2.2 | $9.48 \times 10^5$ | $1.89 \times 10^{-3}$ |
| 2.4 | $5.53 \times 10^5$ | $2.58 \times 10^{-3}$ |
| 2.6 | $3.50 \times 10^5$ | $3.44 \times 10^{-3}$ |
| 2.8 | $2.35 \times 10^5$ | $4.47 \times 10^{-3}$ |
| 3.0 | $1.66 \times 10^5$ | $5.69 \times 10^{-3}$ |
| 3.2 | $1.21 \times 10^5$ | $7.14 \times 10^{-3}$ |
| 3.4 | $9.12 \times 10^4$ | $8.85 \times 10^{-3}$ |
| 3.6 | $7.02 \times 10^4$ | $1.09 \times 10^{-2}$ |
| 3.8 | $5.50 \times 10^4$ | $1.33 \times 10^{-2}$ |
| 4.0 | $4.37 \times 10^4$ | $1.61 \times 10^{-2}$ |
| 4.2 | $3.51 \times 10^4$ | $1.96 \times 10^{-2}$ |
| 4.4 | $2.84 \times 10^4$ | $2.37 \times 10^{-2}$ |

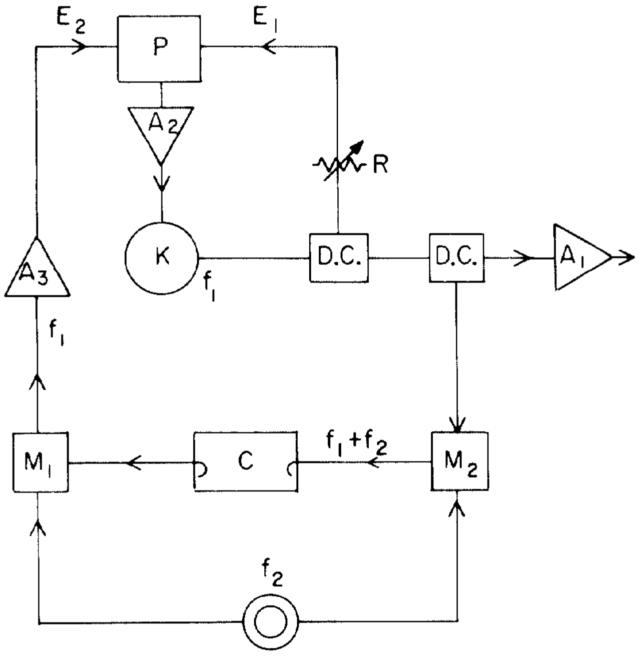

Fig. 1. RF signal source using a superconducting cavity and frequency synthesizer as reference elements. Legend: $A_1$, $A_2$, $A_3$ = amplifiers; C = superconducting cavity; DC = directional coupler; K = reflex klystron; $M_1$, $M_2$ = mixer; O = frequency synthesizer; P = quadrature hybrid acting as phase meter; R = variable attenuator.

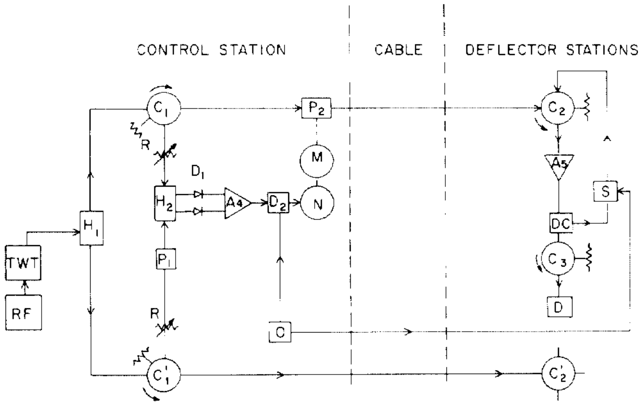

Fig. 2. Block diagram of microwave system for superconducting RF beam separator. Legend: $A_4$ = differential amplifier; $A_5$ = klystron amplifier (plus triode amplifier in series); $C_1$, $C_2$ = four port circulator; $C_3$ = circulator; $D_1$ = crystal diodes; $D_2$ = synchronous detector; D = deflector; DC = directional coupler; $H_1$ = power splitter; $H_2$ = phase bridge; M = motor; N = polarized relay with snap action; O = 1 kHz source; $P_1$, $P_2$ = phase shifter; R = variable attenuator; RF = signal source; S = microwave switch; TWT = traveling wave tube amplifier.

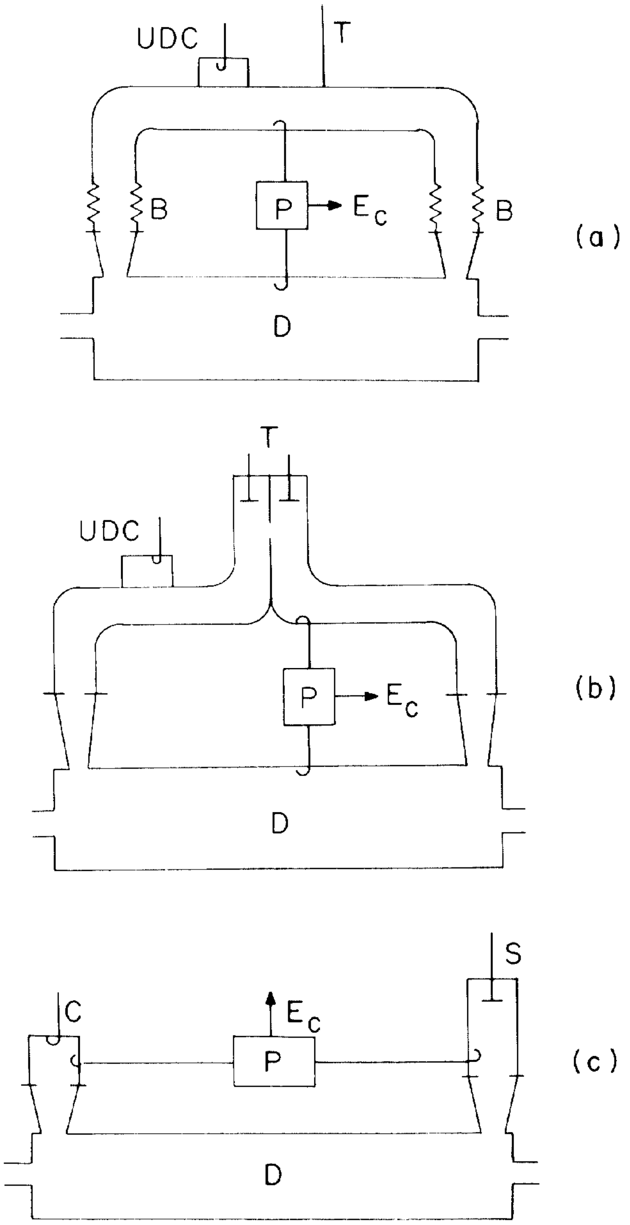

Fig. 3. Possible configurations of resonant deflector: (a) Resonant ring with bellows, (b) resonant ring with phase shifter, (c) resonant cavity with variable short to obtain frequency adjustment. Legend: B = lead-plated stainless-steel bellows; C = coupling loop; D = deflector; P = phase meter; S = variable short; T = piston; UDC = unidirectional coupler.

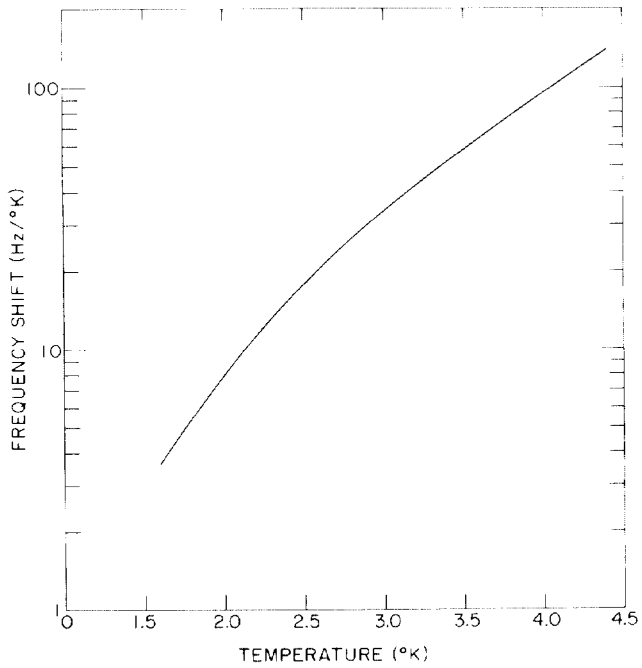

Fig. 4. Frequency shift per °K temperature change versus operating temperature.