DESIGN PROBLEMS IN SUPERCONDUCTING RF BEAM SEPARATORS*

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I. INTRODUCTION

Rf beam separators have now been used in high energy physics research for several years both at Brookhaven and at CERN. They have extended the range of experiments from 6 GeV/c (practical limit of electrostatic separators) to over 20 GeV/c. The magnitude of the deflecting field necessary for successful production of separated beams in this momentum range requires a large amount of microwave power. As a result short pulse operation only is possible, limiting the experiments to bubble chambers. The increased intensity of the converted AGS will make separated counter beams desirable in a few years. Counter experiments require long pulse or CW operation which must be achieved with unconventional techniques. At the present time the very low power losses of pure superconductors appear to provide a unique solution to the problem.

There are several important properties that the superconducting material must possess to be usable in rf separators. The most important are:

1) Low surface resistance, which depends on the intrinsic parameters of the material and the metallurgical condition of the surface.

2) High ac critical magnetic field.

3) High critical temperature.

4) High voltage level at which breakdown or appreciable field emission occurs.

5) Possibility to construct a complicated iris-loaded structure.

Extensive research on the rf properties of pure lead and niobium has, therefore, been conducted at several laboratories involved in the design studies of either linacs or rf separators. Their results were discussed in previous sessions at this Summer Study. In this paper we shall be concerned primarily with practical problems existing in the Panofsky-Schnell type of rf separator employing two superconducting cavities.

Although there are many similarities between the rf separator and the electron linac the design philosophy differs considerably. The main difference stems from the field configuration of the HEM_{11} mode as compared to the symmetrical TM_{01} mode of linear accelerators.[1] A very important practical difference is the absence of beam loading, which permits a simpler design of the coupling mechanism, the transmission line system and the driver amplifier. Furthermore, since the total transverse momentum gain for the proposed separator is about 10 MeV/c per deflector for a period of ~ 200 msec, the device would still be very useful for physics experiments even if the power dissipated were considerably larger than anticipated. Hence the rf separator appears to be the ideal device on which to test superconductivity at high frequencies.

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[1] H. Hahn and H.J. Halama, Rev. Sci. Instr. 36, 1788 (1965).

Before we start considering various design approaches of practical systems in some detail, let us write down the principal parameters of the proposed Brookhaven superconducting separator (Table I), for which the beam design is being carried out by Brown.[2] The design momentum p_o refers here to the highest momentum at which two-contaminant rejection takes place. Useful purified counter beams can, however, be realized up to 20 GeV/c. The selection of a rather high frequency f_o = 2.86 GHz is dictated primarily by the available space in the AGS experimental area. The choice of the rest of the parameters is the subject of this paper.

TABLE I

Principal Parameters of Superconducting Rf Beam Separator

Design momentum, p_o	16 GeV/c
Design wavelength, λ_o	10.5 cm
f_o	2.86 GHz
Interdeflector spacing, L	62 m
Beam hole diameter, 2a	4.2 cm
Deflector length	3 m
Deflecting field, E_o	4 MV/m
Group velocity, v_g	- 0.04 c
Shunt impedance, R_{SW}	5×10^{11} Ω/m
Improvement factor, I	5×10^4
Operating temperature	1.85^oK
Duty factor	CW
Dissipated power	100 W
Refrigerator input power	300 kW

II. GENERAL DESIGN CONSIDERATIONS

In this section we will investigate the effects of operating frequency, improvement factor and peak field on the design of a separator.

The selection of operating frequency plays a very important part in the deflector design and a lower frequency offers some outstanding advantages:

1) Since $Q_o \propto \lambda_o^2$, a large saving in the cryostat and operating costs is realized.

2) A larger ratio of excited-to-unexcited cell length in the AP structure is possible, resulting in increased shunt impedance and smaller peak fields.

3) Larger beam hole results in larger acceptance.

4) Larger absolute tolerances.

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[2] H.N. Brown, these Proceedings, p. 136.

5) Larger surface area for power dissipation.

6) Easier plating.

The disadvantages of a lower frequency would be the higher cost of material which is important if niobium is used, and the required longer interdeflector distance which becomes considerable at high momenta.

The success of the superconducting rf separator will ultimately depend on reducing the rf losses in the deflecting cavities. This reduction is most readily expressed by the improvement factor $I = Q_0/Q_{cu\,300}$. Improvement factors $> 10^5$ have been achieved in simple structures with either plated lead or solid Nb below 2°K. If the same figures are reached in more complicated structures such as iris-loaded waveguides, the total rf power dissipation in the proposed deflectors will be less than 100 W. Since the surface resistance decreases rapidly as the temperature is lowered below T_c, the superconducting materials with high T_c such as Pb, with $T_c = 7.2°K$, and Nb, with $T_c = 8.8°K$, must be selected. Furthermore, the low temperature also improves the frequency stability and insures adequate cooling of the structure due to the superfluid phase of helium below the λ-point (2.18°K).

The equivalent deflecting field is limited either by H_{c1} or the peak electric field at which a breakdown or appreciable field emission occurs. H_{c1} depends on temperature, T, according to

$$H_{c1} = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right] \quad . \tag{1}$$

$H_c(0)$ for Pb $\approx$ 800 G and $H_c(0)$ for Nb $\approx$ 1960 G. The ac critical field of type I superconductors[3,4] does not differ significantly from H_{c1}. This is not, however, the case for Nb, a type II superconductor, where significantly smaller values in the range of 261 to 436 G have been measured.[4]

The peak electric field, $\hat{E}$, at which appreciable field emission or breakdown occurs, is strongly dependent on the surface condition. No limitation in $\hat{E}$ was observed in Nb. The only published value for lead-plated iris-loaded cavities is ~ 15 MV/m and will therefore be considered as a limit on the strength of the deflecting field.[5] It should, however, be mentioned that the Karlsruhe group measured no appreciable field emission below 20 MV/m in a coaxial cavity.[6] Until more data are gathered on plated lead, we will adopt the pessimistic limit of 15 MV/m. The ratio $\hat{E}/E_0 = 5.1$ was measured for the Brookhaven deflector[7] having irises with square edges. The AP structure proposed in the present design reduces $\hat{E}/E_0$ to ~ 3.6, limiting the equivalent deflecting field E_0 to 4.2 MV/m for Pb. In the case of Nb the estimated ratio $\hat{B}/B_0$ yields an equivalent deflecting field of 3.6 MV/m.

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3. J.P. Turneaure, Stanford University Report HEPL 507 (1967).
4. J.P. Turneaure and I. Weissman, J. Appl. Phys. 39, 4417 (1968).
5. H.A. Schwettman, P.B. Wilson, and G.Y. Churilov, in Proc. V Intern. Conf. High Energy Accelerators, Frascati, 1965, p. 690.
6. W. Jüngst, these Proceedings, p. 127.
7. H. Hahn and H.J. Halama, Brookhaven National Laboratory, Accelerator Dept. Report HH/HJH-3 (1963).

III. DESIGN AND OPTIMIZATION OF THE DEFLECTOR

1. AP Structure

When designing a deflector one has a choice of standing wave (SW), or traveling wave (TW), operation. To take advantage of the very low losses in superconductors the group velocity of TW structures would have to be made extremely small. The resonant ring appears to be the only solution, which entails, however, many mechanical problems. Besides, there is the danger of launching the waves in both directions and the adjustment of the amount of coupling is difficult. The main attraction of the ring is the fact that

$$R_{SW} = \tfrac{1}{2} R_{TW} \quad , \tag{2}$$

implying that only one-half of the rf power is required for the same deflection

$$p_T = q \left(R_{SW} \; P \; \ell\right)^{\frac{1}{2}} \quad . \tag{3}$$

A design using a resonant ring system was published earlier where UP (uniform periodic) structures operating at 1.2 GHz were used.[8,9] The complications mentioned put the above system in an unfavorable position as compared to the AP (alternating periodic) cavity approach where significant gains are made in the shunt impedance.[10] Moreover, the existence of unexcited cells makes it very attractive for the construction of superconducting cavities.[11]

The expressions for R/Q, shunt impedance and peak field in AP deflectors were worked out by Hahn who used a TM_{11} small pitch approximation with infinitely thin irises.[12] The results are summarized in Figs. 1, 2 and 3. It is apparent that the best R, as well as $\hat{E}/E_0$, are achieved with the smallest beam hole, ka, and the smallest coupling cell while maintaining the confluent condition. In practice the cell dimensions will be limited by multipactoring distance and manufacturing requirements. Model work based on these data will start shortly to determine the final dimensions.

Due to the narrow bandwidth of superconducting cavities a large group velocity should be selected to decrease the tolerances on the cavity dimensions. Figure 4 shows that this is attained by choosing either a large beam hole, $ka > \sqrt{3}$, resulting in a positive group velocity or the maximum negative group velocity. Positive v_g yields larger acceptance, but smaller shunt impedance, and higher peak fields. Besides, some problems of degeneracy may be encountered in the dispersion diagram and the beam tube terminating the deflector would no longer form a below-cutoff waveguide. In short, the backward wave solution seems preferable.

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8. H. Hahn and H.J. Halama, IEEE Trans. Nucl. Sci. NS-14, No. 3, 356 (1967).
9. H.J. Halama and H. Hahn, ibid., p. 350.
10. H. Hahn, Brookhaven National Laboratory, Accelerator Dept. Report AADD-139 (1968).
11. J.N. Weaver, T.I. Smith, and P.B. Wilson, IEEE Trans. Nucl. Sci. NS-14, No. 3 345 (1967).
12. H. Hahn, to be published in the Proc. 6th Proton Linear Accelerator Conference, Brookhaven National Laboratory, May 1968.

2. Optimization

When designing an rf separated counter beam, the maximum number of wanted particles is desirable. An optimization for maximum transmission and most economical operation was performed indicating a beam hole $2a = 6.4$ cm.[12] In the over-all beam design, however, the acceptance is generally not limited by the deflecting cavities as the particles are in focus when traversing the cavities. The above beam hole would therefore not be filled due to the smaller acceptance of the beam optics; this results in unnecessary power waste. From the point of view of the deflector designer the most important parameters to be optimized are shunt impedance R_{SW}, $\hat{E}/E_o$ and v_g. As seen from Figs. 2, 3 and 4 maximum R_{SW} and minimum $\hat{E}/E_o$ are realized with a smaller beam hole. Maximum negative v_g of ~ 0.04 occurs at $2a \approx 4.2$ cm and has been chosen in the present design.

3. Stability Considerations

The bandwidth (BW) of a resonant cavity depends on the unloaded Q_o and the coupling coefficient $\varkappa$ according to

$$BW = \frac{f_o (1 + \varkappa)}{Q_o} . \tag{4}$$

Large BW is desirable from the point of view of amplitude stability and large Q_o is necessary for economical operation. Maximum value of $\varkappa$ is governed by the available power from the driver, P_s, according to

$$P_s = \frac{(\varkappa + 1)^2}{4\varkappa} P_{rf} , \tag{5}$$

where P_{rf} is the power dissipated by the cavity. Consulting Table I and assuming a driver power of $<$ 1 kW, we obtain $\varkappa \approx 20$, $Q_L \approx 4 \times 10^7$ and BW $\approx$ 70 Hz. Obviously the deflectors cannot be produced within the tolerances corresponding to the bandwidth and it must be possible to tune them to the frequency of a common signal source. AP structures, transformed into cavities by placing shorts at either end, are ideally suited for tuning, by adjusting the position of movable shorts (Fig. 6) which changes their over-all length.

Once the cavities are tuned, the principal drift in the resonant frequency will be caused either by a temperature and pressure fluctuation or by mechanical vibrations. The effect of temperature is twofold:

a) The variation of the surface reactance causes frequency variation according to

$$\frac{\Delta f}{\Delta T} = \frac{1}{2} \frac{r_\infty f_o}{Q r_s} \frac{\Delta(X/r_\infty)}{\Delta T} , \tag{6}$$

where r_∞ is the surface resistance in the extreme anomalous limit and $\Delta(X/r_\infty)/\Delta T$ is the change of surface reactance with temperature. $\Delta f/\Delta T$ is plotted in Fig. 5 for 1.3 GHz and 2.85 GHz. It is evident that one must work at temperatures below 2^oK where $\Delta f/1^oK < 36$ Hz.

b) Mechanical dimensions also change with temperature, resulting in frequency changes. The expansion coefficient of Cu at 2^oK is $6 \times 10^{-10}/^oK$, (Ref. 13), corresponding to 1.7 Hz/^oK. This value is small compared to the reactive Δf and can safely be neglected.

The frequency shifts caused by changes in pressure will depend on the mechanical rigidity of the structure and will have to be determined experimentally. Schwettman et al.[13] measured $\sim 0.9 \times 10^{-8}\ f_o$ for a change of 1 mm Hg at 2°K.

Successful separation of particles will depend on the cancellation of unwanted particles.[14] This is achieved by equal amplitudes of electromagnetic fields and zero phase slip in both deflectors and by the proper phase relationship between the deflectors. Let us permit a variation of 1% in the amplitude, i.e., for $E_o/E_1 = 1.01$ we obtain

$$\Delta f = \frac{f}{2Q} \sqrt{\left(\frac{E_o}{E_1}\right)^2 - 1} \approx 5 \text{ Hz} \quad . \tag{7}$$

The allowable Δf of 5 Hz requires a temperature control of 0.15°K which can be met without difficulty.

Nonsynchronism between the wave and the traversing particles gives rise to a phase slip, φ, and the deflection is reduced to

$$\frac{\sin \frac{1}{2} \varphi}{\frac{1}{2} \varphi} \approx 1 - \frac{1}{24} \varphi^2 \quad . \tag{8}$$

Letting Eq. (8) = 0.99 establishes the limit on $\varphi \leq 0.5$.

φ is related to the tolerances on the inside diameter 2b by

$$\varphi \approx k\ell \frac{c}{v_g} \frac{\Delta\, 2b}{2b} \quad , \tag{9}$$

resulting in $\Delta\, 2b \approx 15$ µm. It is desirable to hold the tolerances on 2b as close as possible. The difference in the resonant frequency of the excited cells due to an unequal diameter 2b will introduce electric fields in the unexcited cells and thus impose a limit on their width. This in turn will adversely affect both R_{SW} and $\hat{E}/E_o$ (Figs. 2 and 3).

Finally, the most stringent tolerances are required by the frequency stability of the individual cells during operation since a mechanical change of 1 Å produces a change of 2 Hz.

4. Practical Considerations

Two materials are being considered for the construction of the iris-loaded cavities, namely solid niobium and lead-plated copper. The material selected will determine not only the method of manufacturing but also some mechanical dimensions, in particular the relative length of the cells. At the present time we favor the lead-plated

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[13] H.A. Schwettman, J.P. Turneaure, W.M. Fairbank, T.I. Smith, M.S. McAshan, P.B. Wilson, and E.E. Chambers, IEEE Trans. Nucl. Sci. NS-14, No. 3, 336 (1967).

[14] H.W.J. Foelsche, H. Hahn, H.J. Halama, J. Lach, T. Ludlam, and J. Sandweiss, Rev. Sci. Instr. 38, 879 (1967).

copper cavities due to easier machining, surface preparation, lower cost and higher ac magnetic field. However, rapid progress in niobium as reported at this Summer Study might soon change the picture.[15-17]

Copper modules consisting of one excited cell plus two small half cells (Fig. 6) will either be electroformed or machined. In the case of Nb much longer sections can be produced. If machining is employed the excited cells will be joined by Cu diffusion under pressure. The modules will be individually measured and brought to the same dimensions by electropolishing. By this method, controlled removal of copper can be achieved in the micrometer range. To prevent the rotation of fields, mode stabilizers in form of flat will be used in electroformed cavities while holes can be employed in brazed cavities. The modules will be plated in a lead fluoborate bath using our standard method.[18]

After the assembly with cryogenic gaskets in the unexcited cells the frequency of both deflectors should be within 20 kHz, which corresponds to a total length change of ~ 0.5 mm. The more closely we can match the resonant frequencies of the deflectors, the less field we shall have in the unexcited cells.[19] When the deflectors reach their operating temperature of 1.85°K, their resonant frequencies must be adjusted to within 5 Hz. This is accomplished by a variable short S_1 (Fig. 6) which is coupled to the main cavity. By moving the short, the reactance of the last cell is changed, thus changing the over-all resonant frequency of the deflector. At unity coupling a displacement of S_1 by 1 mm corresponds to 40 kHz. With a coupling of 10^{-2} the adjustment range of the resonant frequency of each deflector is approximately 20 kHz.

In a previous section we derived a permissible temperature variation of ~ 0.15°K corresponding to a variation of ~ 10 mm Hg at an ambient pressure of ~ 15 mm, which is relatively easy. The most difficult problem rests in the mechanical stability. A pressure change of 1 mm Hg on a long cylinder with comparable dimensions to the deflector corresponds to a frequency shift of ~ 28 Hz.[20] Irises will without doubt stiffen the deflector considerably and alleviate some difficulty in the pressure control. The decoupling of the deflectors from their surroundings to reduce vibrations will require an ingenious mechanical solution.

Most of the variations can be corrected by a servo loop since the shortest time in which they can occur is of the order of the time constant $\tau > 2$ msec. For this purpurpose, another short S_2 (Fig. 6) is provided with a coupling of 10^{-4}, having an adjustment capability of ~ 200 Hz. The servo loops will be treated in the next section.

Identical fields in both deflectors will be adjusted for maximum bandwidth by a similar coupling mechanism used in all our superconductive tests,[21] namely a below-cutoff attenuator (A in Fig. 6). A stainless-steel coaxial cable plated with 5-10 μm of Cu (skin depth at 3 Gc ≈ 1 μm) can be adjusted from the outside of the Dewar for

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[15] J.P. Turneaure, presented at this Summer Study (unpublished).

[16] I. Weissman, these Proceedings, p. 32.

[17] R.W. Meyerhoff, ibid., p. 23.

[18] H. Hahn, H.J. Halama, and E.H. Foster, ibid., p. 13.

[19] T.I. Smith, presented at this Summer Study (unpublished).

[20] E.H. Foster, private communication.

[21] H. Hahn, H.J. Halama, and E.H. Foster, in Proc. 6th Intern. Conf. High Energy Accelerators, Cambridge, Mass., 1967, p. A-139.

the required amount of coupling. Standard 7/8 in. cable has an attenuation of 8.5×10^{-2} dB/m at 3 GHz, negligible heat leak, and is safely rated for 1 kW operation.

IV. MICROWAVE SYSTEM

Several systems were investigated in the course of the last two years.[9] The solution adopted here uses a centrally located signal source common to both deflectors and seems to be the most economical. A stable and yet adjustable frequency source[14] is provided by a phase-locked oscillator shown in Fig. 7. The required frequency stability of 1×10^{-9} is surpassed by more than one order of magnitude in commercial frequency standards. The multiplied output of the standard is mixed with the output of the oscillator which differs in frequency by a predetermined i.f. The i.f. is compared in phase with a variable signal VFO whose stability as well as FM requirements are reduced by the ratio f_0/i.f. A 2 MHz i.f. with a typical bandwidth of ± 500 kHz will require a VFO of stability $\approx 5 \times 10^{-7}$, which can easily be accomplished by a synthesizer. The detected output from the phase bridge with proper dc amplification and compensation phase-locks the frequency of the oscillator. Here we have a large choice between a BWO, a VTM, a reflex klystron, or a solid-state oscillator. Spurious FM and noise are the most important factors and a narrow bandwidth device is preferable. There are many solid-state sources with excellent specifications as well as low voltage requirements and which are therefore more attractive.

As was pointed out earlier, successful separation depends on the cancellation of unwanted particles.[14] The deflectors must therefore be held in a prescribed phase relationship to within $\pm 1^{o}$. The over-all schematic of the microwave system, including the phase loop, is shown in Fig. 8.

The signal from the rf source is amplified (TWT), split (H_1), and then transmitted along two phase-stable cables to identical deflector stations located 62 m apart. Here the signals are again amplified in a 1 kW klystron (A_5) to a level required by the deflectors. The power amplifier A_5 can either contain its own AGS (automatic gain control) or it can be leveled to a reference signal derived from the deflector.[22] A 1 kW circulator, C_3, absorbs the reflected power caused by high coupling coefficient. A small portion of the drive is coupled out through a directional coupler DC and is subsequently modulated by 1 kHz in a microwave switch.[9] This signal then travels back through C_2 and C_1 to a phase bridge H_2 where it is compared with a similar signal coming from the other deflector station. The output of H_2 contains the information on the phase error between the deflectors. This error signal is amplified (A_4), demodulated (D_2), and then used to drive a line stretcher (P_2). We thus have a zero-seeking servo which keeps the deflectors in the prescribed phase relationship.[14]

Finally, a signal must be provided to determine the on-resonance condition. This can be accomplished by monitoring either the amplitude of the fields in an excited cell or the phase shift across the deflecting cavity, by coupling out small signals. The difference in phase across the cavity drifting off resonance is sensed in a phase bridge and the error signal is used after proper amplification to actuate a servo circuit which drives a short, S_2 in Fig. 6. For a faster control the short can be replaced by a varactor at room temperature. The reactance of the varactor diode is controlled by the error signal to restore the resonant condition.

The duty factor of the rf separator will be determined by the length of the spill of the AGS beam. The driver power can be reduced by a factor of 10 between the pulses to save refrigeration, while the phase loops can remain operative. A duty factor ≤ 0.3 can be anticipated for the converted AGS, which will of course proportionally reduce the power requirements.

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[22] L.R. Suelzle, these Proceedings, p. 67.

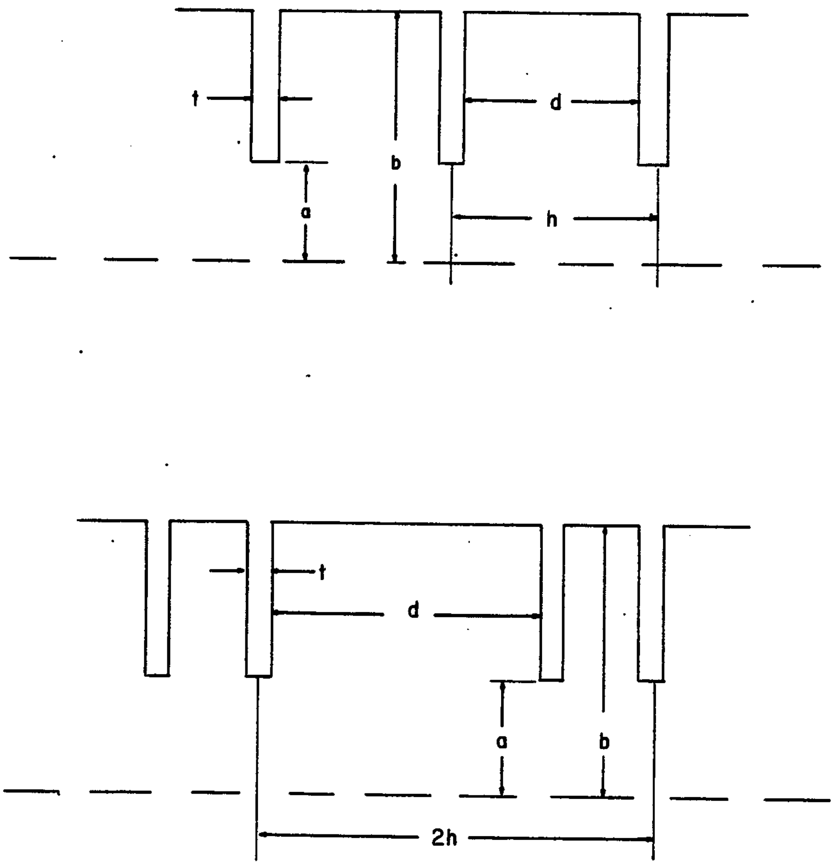

Fig. 1. Geometry of alternating periodic structure.

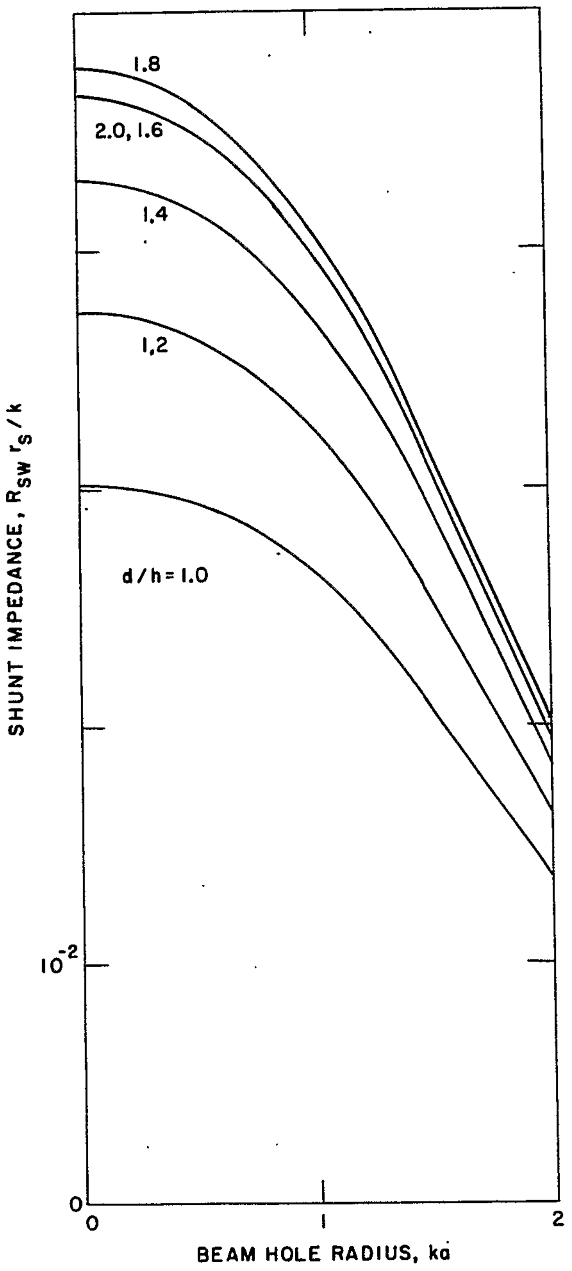

Fig. 2. Shunt impedance of deflector cavity vs beam hole radius.

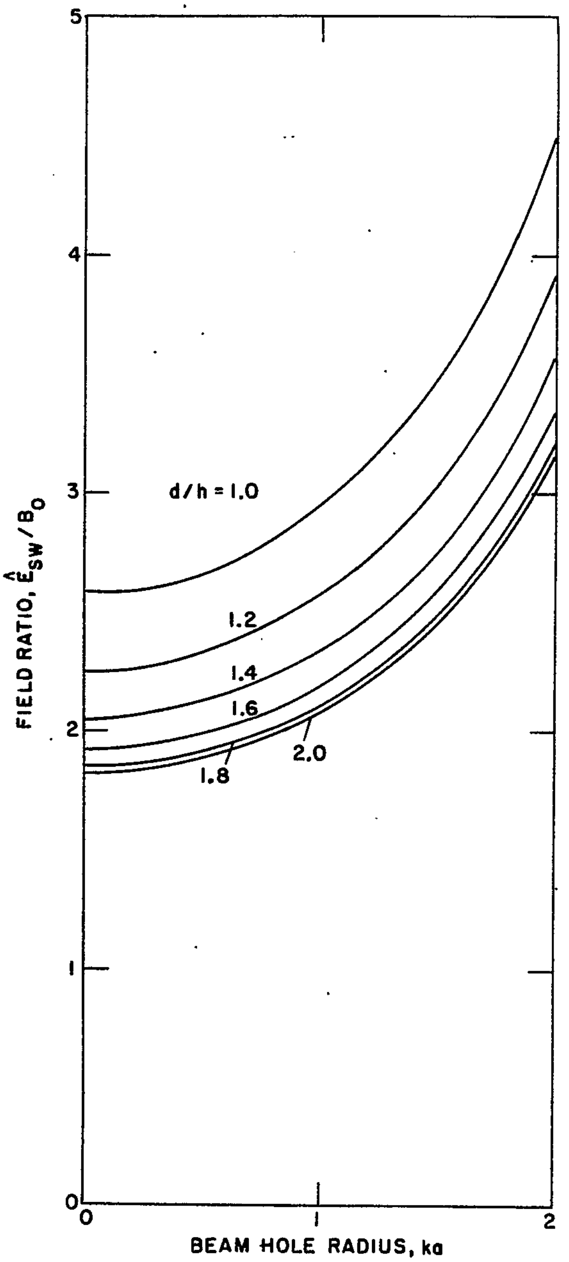

Fig. 3. Ratio of peak electric field to average deflecting field vs beam hole radius.

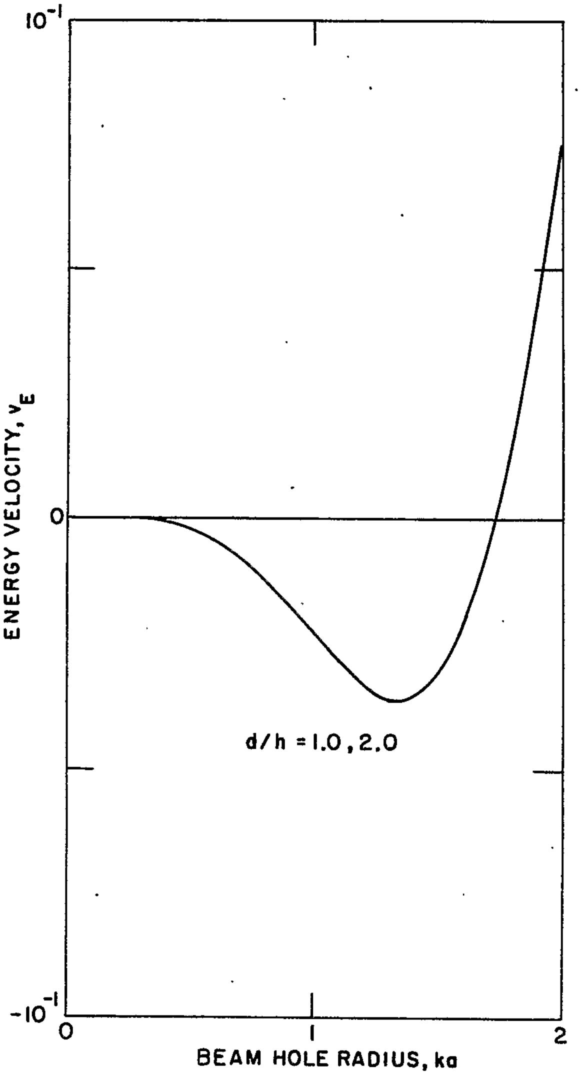

Fig. 4. Group velocity vs beam hole radius.

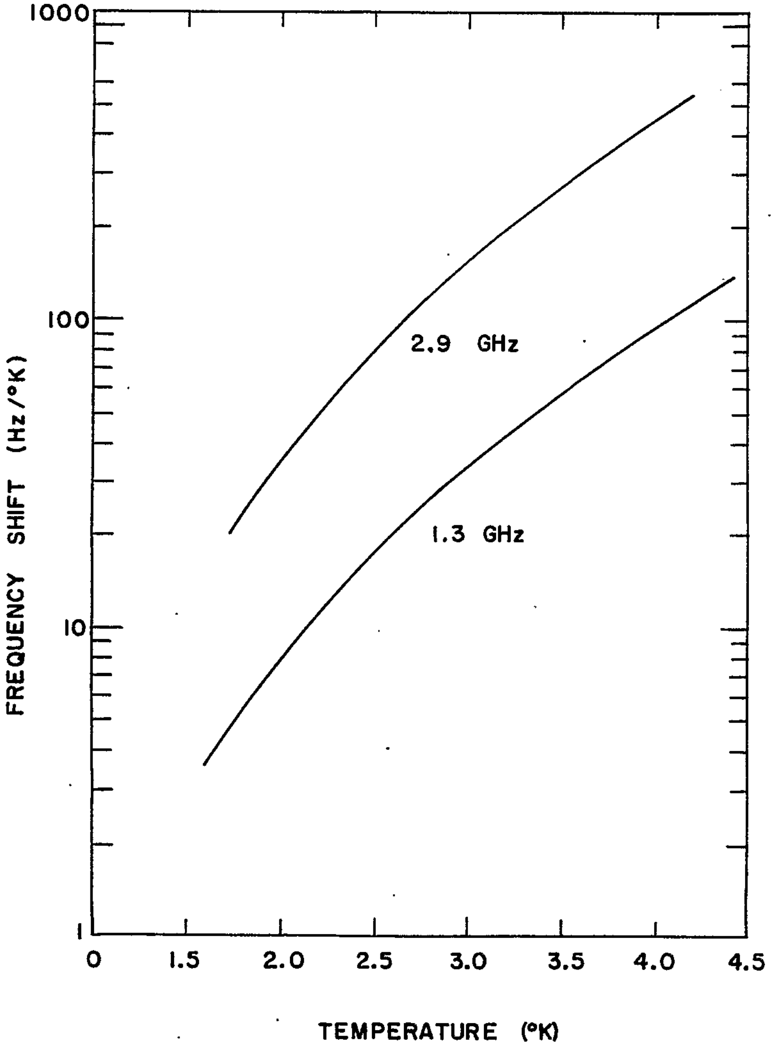

Fig. 5. Frequency shift per ^{o}K vs operating temperature.

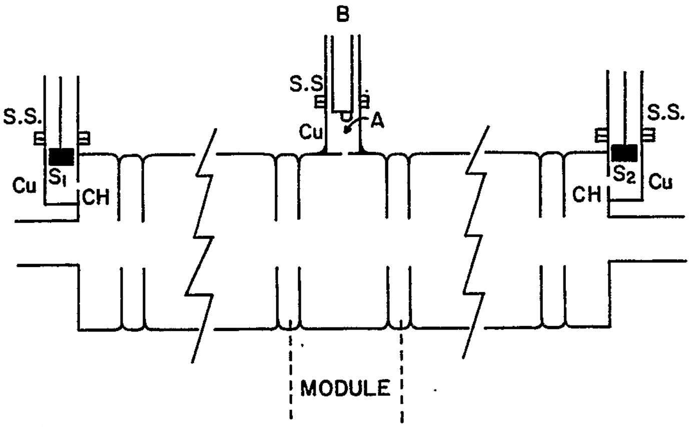

Fig. 6. Schematic of deflecting AP cavity. Legend: SS = stainless steel, Cu = copper, CH = coupling hole, S_1 and S_2 = variable shorts, A = below-cutoff attenuator, B = stainless steel copper-plated cable.

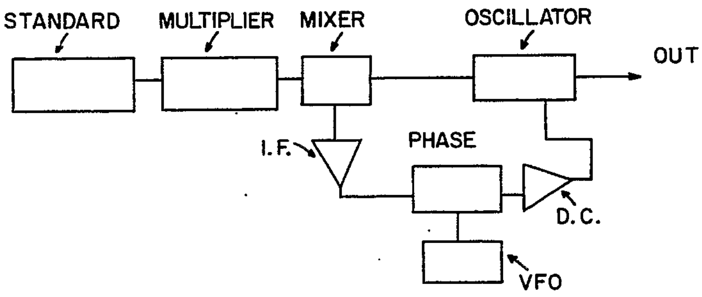

Fig. 7. Block diagram of phase-locked source.

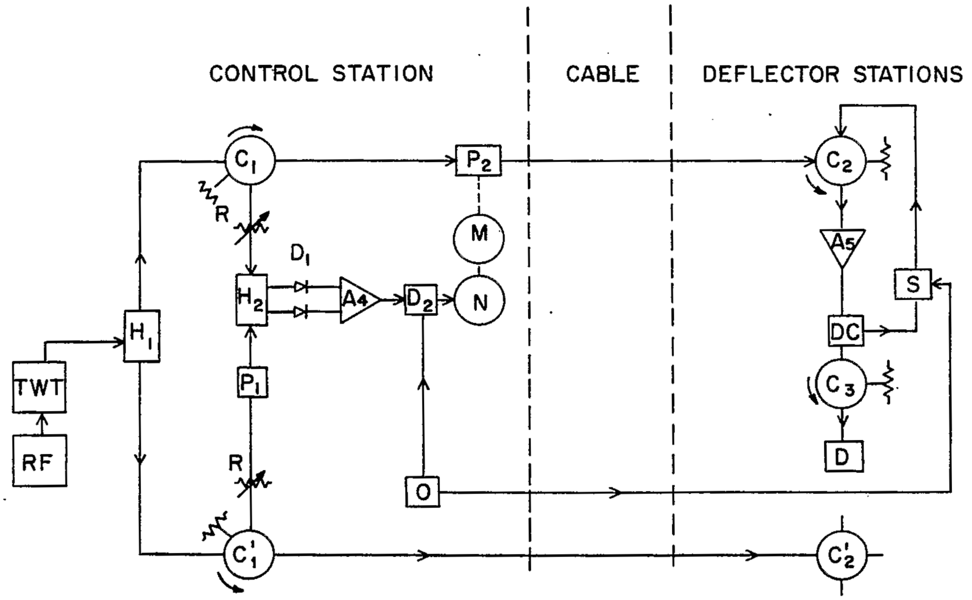

Fig. 8. Block diagram of microwave system for superconducting rf beam separator. Legend: A_4 = differential amplifier, A_5 = klystron amplifier, C_1 and C_2 = four-port circulator, C_3 = circulator, D_1 = crystal diodes, D_2 = synchronous detector, D = deflector, DC = directional coupler, H_1 = power splitter, H_2 = phase bridge, M = motor, N = polarized relay with snap action, O = 1 kHz source, P_1 and P_2 = phase shifter, R = variable attenuator, RF = signal source, S = microwave switch, TWT = traveling wave tube amplifier.