THE APPLICATION OF SUPERCONDUCTIVITY TO R.F. PARTICLE SEPARATORS

1. Introduction

The purpose of this note is to discuss the advantages and feasibility of a superconductive R.F. separator, and to assess whether it is of interest for CERN to start on some small scale experiments in 1963.

The R.F. separator at present under construction is used as a basis for comparison with a possible superconductive separator. This comparison is justified because most of the essential parameters of the present separator (frequency, aperture, R.F. power) are believed to be near to optimum for CFS momenta, existing beam transport units and site conditions, despite the fact that these parameters were largely decided by the availability of high-power R.F. sources. In most of this report it is assumed that the R.F. separator becomes really interesting for momenta above 8 GeV/c, and that below this momentum the conventional electrostatic separator is adequate or even preferable. This assumption may not be valid for a superconductive separator, but we will nevertheless suppose that the applications at higher momenta are the ultimate goal, since it is in this region that the R.F. separator has at present no competitor.

2. Limitations of the present R.F. Separator

The most important limitation is the duration of the R.F. pulse, around 10 microseconds, which makes the separator useful principally for bubble chamber work, and demands fast, single-traversal target operation. At 'S'
band wavelengths (≈ 10 cm) there seems to be little hope of obtaining high R.F. powers (10–20 MW) with substantially longer pulses in the foreseeable future. At 'L' band (≈ 23 cm) pulse lengths of one or two milliseconds are obtainable at powers of 5 to 10 MW, but the increase in flight path necessary makes the 'L' band separator less attractive for separation at high momenta.

A second, though less serious, limitation is the aperture available in an 'S' band deflecting structure. The present R.F. separator is slightly aperture limited in one transverse plane by the deflecting structure and in the other plane by the existing CERN quadrupoles. Larger aperture quadrupoles might marginally favour a longer wavelength for the separator, but at high momenta the available flight path from the CPS would still be a limitation.

It seems fair to suppose therefore, that the one major improvement of interest for the higher CPS momenta would be a substantial increase in the duration of a separated particle beam, so that an R.F. separator would be equally useful for bubble chamber, spark chamber and counter beam. An R.F. separator using superconductive deflecting structures could in principle permit such long pulse operation.

3. Applications of a Superconductive R.F. Separator

It seems rather early to judge where, in three or four years time, a superconductive separator would best fit into the nuclear physics research programme. The essential features of C.W. or long pulse operation, combined with a substantially greater separation per unit length than can be obtained with E.S. separation suggest the following examples

3.1. Momenta between 10 and 20 GeV/c

A considerable increase in particle flux will accompany the present trend of designing secondary beams for smaller production angles. At zero
production angle, present CPS intensities, 15 GeV/c, ± 1 o/o momentum bite and 10^{-4} steradian acceptance, one could have nearly 10^6 pions in a 100 msec burst. To define such a \pi^+ beam from the proton background is beyond the limit of existing counter techniques and would be a legitimate application of a long pulse R.F. separator.

3.2. Low momentum K beams

The inherently greater separation per unit length of the R.F. as compared with the E.S. separator offers the possibility of producing high intensity separated K beams. The more modest R.F. power requirements at lower momenta suggest this as a possible first application of a superconductive separator.

3.3. Separators for future ultra-high energy machines

The R.F. separator is the only feasible means known at present for mass discrimination in the 100 GeV/c region. Keil has shown (AR/Int. PSep/62-3) that the arguments in favour of long pulse operation are even stronger in this case than in 3.1 above.

4. Superconductive Resonant Cavities at 'S'-Band

Recent work at Stanford (Perry B. Wilson, HEPL-262, Investigation of the 'Q' of a Superconducting Microwave Cavity) described at the 1962 H.E. Instrumentation Conference, has produced some encouraging results. A 'Q' of \( 3 \times 10^8 \) has been measured at 2856 MHz for a lead-plated TE_{011} mode cavity cooled to 1.80 K. The R.F. power input was around 3 W.

Wilson plans to excite the cavity up to about 1 kW in the near future, to investigate probable quenching of R.F. superconductivity due to the magnetic field. If quenching at microwave frequencies does not take place at magnetic fields substantially below the DC quenching field, there should be no fundamental limitation here for R.F. separators, since in the types of R.F. structure of interest, the required deflection forces are produced for
magnetic fields of 200-300 oersted at the conducting walls. This is comfortably below the DC critical field for a number of superconductors.

5. **R.F. Power Requirements**

The 'Q' of $3 \times 10^8$ measured in a $\text{TE}_{011}$ cavity corresponds to a factor of about 3000 above the normal 'Q' of a copper cavity at room temperature in the same mode. If we were to assume that a similar factor could be achieved in a more complicated loaded structure, about 5 kW peak would be required for a superconductive structure (compared with $\approx 15$ MW for a normal structure) to give a transverse impulse of 20 MeV/c to a particle beam. CW klystrons of at least 1 kW already exist at S-band, so the R.F. power source presents no fundamental difficulty. The cryogenic requirements turn out to be more exacting however, and show that the highest 'Q' value is not necessarily the most important factor.

6. **Heat Losses at a Few Degrees K**

Before considering the implications of R.F. power loss, it is convenient to estimate the heat transfer due to imperfect thermal insulation of a superconductive deflecting structure. We consider first the radiation transfer as this is likely to be predominant in practical cases. For a superconductive deflecting structure, similar in size to that of the CERN R.F. separator, surrounded by a radiation shield at liquid nitrogen temperature ($\approx 77^\circ K$), one could expect to reduce the radiation transfer to about 0.2 Watt for the necessary surface area of about 2 m$^2$. This is a very low figure and, for example, corresponds to the vaporisation of about 0.25 litre of liquid helium per hour at 4.2$^\circ K$. The conduction heat transfer through supports is not likely to exceed this figure, but one could be very conservative and assume a total heat loss of 1 Watt without making much demand on the refrigeration system.
7. R.F. Power Dissipation

The power of 5 kW deduced in section 5 could not be dissipated continuously without requiring excessive refrigeration power. The reversible thermodynamic efficiency for pumping heat from $1.8^0\text{K}$ to $300^0\text{K}$ is 0.6 o/o, and, allowing 10 o/o mechanical efficiency in the refrigerator, some 1700 W of compressor power would be required per watt of heat pumped out at $1.8^0\text{K}$.

There is, however, a much more serious problem associated with operation at $1.8^0\text{K}$. To reach this temperature it is necessary to pump away helium gas at a rate sufficient to maintain a pressure of about 12 Torr. Even for a few tens of watts mean dissipation, the vacuum pumps and heat exchangers would have to handle a throughput of several thousand cubic metres per hour, requiring a very large and costly installation indeed. From these considerations alone it is clear that any practical superconductive separator would operate at or near $4.2^0\text{K}$.

At $4.2^0\text{K}$ Wilson's measurements show a factor of 1300 over the normal 'Q' for copper at room temperature. The peak R.F. power required for 20 MeV/c transverse impulse is now increased to 8.3 kW, but the reversible thermodynamic efficiency is increased to 1.4 o/o, requiring only about 700 W compressor power per watt of heat pumped, at 10 o/o mechanical efficiency. Thus for a given transverse impulse, the compressor power required is less for operation at $4.2^0\text{K}$ than at $1.8^0\text{K}$, despite the lower 'Q' value at the higher temperature.

Nevertheless it is clear that one could hardly consider dissipating 8.3 kW average R.F. power at $4.2^0\text{K}$, so such a separator working in C.W. regime is out of the question, with these figures at least. For long pulse operation, however, the situation looks much more promising.
The 'Q' of the CERN R.F. separator structure is around $12 \times 10^3$; a factor of 1800 improvement due to superconductivity would give a 'Q' of about $2 \times 10^7$. The natural time constant of such a cavity at a frequency of $3 \times 10^9$ Hz is 6.6 millisecond, but by various artifices it is possible to reduce the effective filling time by a useful factor, so we can assume a filling time of 3 msec. If we choose a useful deflection time of 12 msec and a pulse repetition rate of 1 per 3 seconds the duty cycle would be 0.5 o/o. With a peak power of 8.3 kW the mean R.F. power dissipation would be 42 W at 4.2°K, and would require a refrigeration plant consuming some 30 kW of mains power. This is a medium size installation and not by any means unreasonable.

The above example is given to illustrate the orders of magnitude involved, and should not be interpreted too literally. It does show, however, that fairly modest improvements in microwave superconductivity might make such a separator quite a practical project.

8. Beam Loading

In recent proposals for superconductive Linacs one of the major problems discussed has been the loading by the beam, either of the R.F. source due to the work done by the R.F. fields on the particles, or of the refrigeration equipment due to part or all of the beam hitting the supercooled structure.

In a superconductive separator such effects would be quite negligible. Consider, for example, a secondary burst of $10^6$ charged particles at 20 GeV/c lasting 10 millisecond, and suppose the beam receives a deflecting force corresponding to 7 MV m$^{-1}$. The R.F. peak beam loading is then about $10^{-3}$ W m$^{-1}$. Even if the total energy of this burst were dissipated in the supercooled structure the instantaneous power would only be around 3 W and the energy given up during the pulse, 30 millijoule. We can therefore neglect all effects due to beam loading in a superconductive separator of this sort.
9. Discussion of Previous Sections

The rough estimates above show that it should be possible in principle to construct a superconductive R.F. separator even within the limitation of present-day technology. This report should not, however, be considered as a preliminary design proposal, but rather as a justification for undertaking some experimental work in the field of superconductivity at microwave frequencies. No attempt has been made to assess the cost of such a separator, though from the above figures one might guess that it would be somewhat more expensive than the normal R.F. separator but not by a large amount.

In any case, it is probable that the optimum parameters for a superconductive deflector structure would be different from those of a normal one, and simple scaling considerations would not give the best design. Before making any serious attempt to work out a tentative design, it will be necessary to undertake some general research in microwave superconductivity and other relevant fields. In the next section some appropriate topics are discussed.

10. Proposed Experimental Work in CERN

10.1. Superconductive materials

Of the various possible ways of reducing R.F. losses, and hence refrigerator power, the choice of superconductor appears to offer the greatest promise. Up to the present time, most experimental work on microwave superconductivity has been with lead and tin, presumably because these metals are relatively easy to apply. Furthermore the majority of experimental work has been directed towards a better understanding of the superconductive state, rather than a specific practical application. So far there appears to have been few, if any, attempts to use the so-called "hard" superconductive alloys (e.g. niobium-tin) as coatings for resonant cavities. There appear to be some theoretical reasons why such alloys would not work at high frequencies,
and there is certainly considerable technological difficulty in producing uniformly superconductive coatings on large surfaces. Nevertheless, the high transition temperatures and critical fields of many of these alloys make some further investigation in this direction desirable. Pure niobium, with a somewhat higher transition temperature and a much higher critical field than lead, would be, perhaps, a more promising superconductive material for investigation.

The effect of physical and chemical impurities in pure superconductive metals would be an important line of research in this connection, and a substantial reduction in residual surface resistivity could be of considerable practical importance.

10.2. High R.F. Fields

Apart from superconductivity, a possible consequence of operating a resonant cavity at very low temperatures might be a reduced risk of R.F. breakdown. It seems plausible that the factors which permit and initiate R.F. discharges in vacuum would be appreciably less active at low temperatures, and that a combination of ultra-high vacuum, low temperature, special surface finish and, possibly, unusual wave modes could permit much higher R.F. electric fields to be obtained without breakdown. Any substantial success in this direction would have many applications, including the possibility of separating very short lived particles.

10.3. Special Wave Modes

There exist certain resonator and waveguide modes in which the fields at the conducting boundary surfaces are appreciably less than for the more commonly employed modes. One of these, the TE_{01} mode in a circular cylindrical waveguide, is used for long-distance transmission, because of its very low attenuation. This is the lowest mode of its type, but more generally there are higher transverse modes in which the stored energy tends to be concentrated near the axis of the waveguide, thus reducing the fields at the conducting walls.
Such modes are of interest in connection both with superconductive structures and with high R.F. field levels, since in both cases the reduction of field strength at the walls is of primary importance.

Investigations of these modes at shorter wavelengths (e.g. 'X'-band, 3 cm) would be of interest for possible separation in the 100 GeV energy region.

11. Conclusions

There seems to be a strong incentive to start some work in CERN on microwave superconductivity. The most immediate application of this would logically be for R.F. separation of particles, since problems of beam loading do not arise. However, developments in this direction would be of equal importance for any superconductive linac which might be projected.

It would be desirable to start this work, on a small scale at least, some time in 1963. The CERN helium liquifier should be in operation before mid-1963, and will have adequate capacity for the experiments envisaged as well as for other small scale cryogenic work.

The experimental programme on microwave superconductivity must be arranged so as not to interfere with the completion of the R.F. separator at present under construction. This is certainly possible, and there would be no reason to delay the start of this work for fear of slowing up existing projects.

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