SUPERCONDUCTING RF SEPARATOR RESEARCH AT THE RUTHERFORD LABORATORY

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I. INTRODUCTION

Nimrod at the Rutherford Laboratory is a 7 GeV synchrotron, and compared with the CERN PS or the Brookhaven AGS, produces relatively few kaons. In 1966 a preliminary study was undertaken[1] to compare electrostatic (ES) and rf separators for the momentum range 2-5 GeV/c, and even to consider very low momentum beams of less than 1 GeV/c. The comparison was relevant for both bubble chamber beams using the shortest spill time available at Nimrod of about 200 μsec, and also for counter beams of up to about 500 msec duration. The pulse lengths dictate that the rf separators should be superconducting: this is especially obvious for counter beams. Superconducting rf separators operating at L-band frequency offer many advantages over ES beams, in that:

i) They can separate the maximum emittance beam that can be accepted by conventional quadrupoles (ES separators have too low transmission above 2 GeV/c unless the emittance is reduced).

ii) They can use the increased acceptance of superconducting quadrupoles when these become available.

iii) They can provide useful bubble chamber fluxes for momenta up to about 5 GeV/c, and with a larger momentum bite, kaon fluxes of the order 5×10^3 per pulse (for an incident proton beam $\sim 2 \times 10^{11}$ per pulse) for counter beams. Comparison between optimized superconducting and rf beams give the following ratios:

Flux rf/ES = 1.25 at 2.0 GeV/c to 8.0 at 5 GeV/c.

II. THE SEPARATOR SYSTEM

The system envisaged is shown in Fig. 1, and is similar to that in use on the CERN PS. The two cavities will operate at L-band frequency (about 1300 MHz), this frequency being chosen as the familiar compromise between physical size and shunt impedance R, acceptance α, and cavity separation D. These latter quantities all favor lower frequencies; even cavity separation, since here we are dealing with beams of low momentum and require space for intercavity beam transport components. For a central momentum of 2.7 GeV/c, an intercavity phase difference of 180° for K, π separation requires D = 7.5 m, and the system gives useful separation over the momentum range 2.0 to 4.5 GeV/c. If the distance were increased threefold to give ample space, K yield would be reduced due to decay, and the useful momentum band would be reduced to 2.4 to 3.0 GeV/c.

Ideally the imaging system between the cavities provides 1:1 imaging in each plane of the phase-space configuration. Due to the comparatively short distance D, this cannot be achieved unless superconducting quadrupoles are used. If conventional quadrupoles are used, 1:1 imaging can only be achieved in the plane of separation,

1. E.J.N. Wilson, Rutherford Laboratory Internal Memo, NIMROD BP 66/26 (1966).

and this can be obtained by using a single symmetrical triplet. In the orthogonal plane the transfer matrix has two solutions, both of which lead to some beam loss due to blowup: this loss is least (about 10%) for a drift length roughly equal to the intercavity length D.

The choice of L-band frequency results in a large cavity acceptance. Optimization of cavity acceptance alone, based on a maximum equivalent deflecting field of 4 MV/m and a cavity aperture 2a = 10 cm, leads to an optimum cavity length of 3.5 m, and a maximum acceptance of 78.5 mm·mrad. Such cavity lengths leave little space ($\sim$ 4 m) for the intercavity beam components; such an acceptance is much greater than the acceptance of the optimum doublet for momentum selection (see Fig. 1), even if it were superconducting. In fact, cavities of length 1.25 m are adequate, and with these it is reasonable to have the beam parallel inside the cavities.

III. THE SEPARATOR CAVITIES

The cavities themselves will be of disc-loaded waveguide, operating in the uniform-periodic (UP) π mode of the HEM_{11} deflecting mode. In π-mode operation the cavities are fundamentally standing wave, for which there are two main advantages:

i) Resonant chain or ring operation is essential, and for a UP chain, π-mode offers the highest shunt impedance. For a conventional copper structure computed[2] shunt impedances at 1300 MHz, π-mode give 13.2 MΩ/m (2a = 10 cm) and 11 MΩ/m (2a = 11 cm).

ii) The mid-planes of the discs are planes of antisymmetry (i.e., there is zero current) and offer less critical planes for joining cells. An alternative point of view is to regard the structure as an alternating-periodic (AP) structure in $\pi/2$ mode in which the alternate cavities, which contain zero stored energy, shrink to zero. Practical methods of joining the cells may be:

   a) A simple compression joint with an indium seal.

   b) Electron beam welding the lead in the join planes, discussed briefly later.

The disadvantages of π-mode operation in UP structures is the reduced tolerance [proportional to (number of cells)^2 against (number of cells)^1 for AP $\pi/2$-mode structures]. But since the cavities are only 10-11 cells long (L = 1.25 meters, $\ell = \lambda_0/2 = 11.5$ cm), the mode separation is sufficiently large for the tolerances to be manageable. Even though there is a frequency-phase degeneracy for the structure with such large apertures, there is little risk of double-moding, and it can easily be avoided.

The cavities will be of electrodeposited lead on copper, and will operate at 1.85°K. Though the use of niobium offers an exciting alternative, cost precludes its use on this particular project. The theoretical improvement factor I(Pb) $\sim 7 \times 10^5$ at 1.85°K, 1300 MHz, and, because of the variability of lead, a practical figure $I = 10^5$ is aimed at. Field emission limits the maximum equivalent deflecting field to the range 5-7 MV/m: to avoid difficulties a more modest field of 4 MV/m is aimed at.

A deflection of the order 1.5 mrad/cavity is required at 2.7 GeV/c. With $EL = \theta p$, this gives for E = 4 MV/m, L $\sim$ 1 m, i.e. 10 cells/cavity. If it is necessary to reduce the field by some small amount because of field emission, then L must be increased

2. H.G. Hereward and M. Bell, CERN Yellow Report CERN 63-33 (1963).

by the same amount to give the same deflection, and the power $\propto E^2L$ actually decreases. Because the beam is parallel inside the cavities, and because the cavities already have a much larger acceptance, modifications of this kind will not greatly affect the beam design. With $I = 10^5$, $2a = 10$ cm, $P \sim 12$ W/cavity. At a maximum duty cycle of 25% ($\sim$ 500 msec/2 sec), this gives $(2P)_{av} = 6$ W. To this we add an arbitrary 30% due to cavity end-plate and tuner loss, giving a total 8 W. With total cryostat losses of about 2 W, this gives a total refrigerator load of 10 W.

IV. REVIEW OF MEASUREMENTS TO JUNE 1968

Preliminary tests on electron beam welding of lead joints have been made with an outside manufacturer. Electron beam power is seen to be critical (of the order of 30 kV, 8 mA): overheating causes the lead to globulate, underheating does not allow the weld to form. Also the weld does not take if the pressure is allowed to become too high, i.e. greater than 10^{-5} torr. Successful samples show a good uniformity of lead at the join, and are sufficiently encouraging to warrant further study.

It was originally decided to do Q measurements at the final operating frequency to avoid problems with frequency scaling. This view has been changed (mainly due to handling problems) and the major effort is now on S-band cavities. Two copper cavities (one rolled and welded, the other electroformed) have been made for Q tests at 1300 MHz, TE_{011} mode. Both cavities were originally lead-plated (to a thickness 0.001 in.) by an outside manufacturer by a "standard" commercial process (0.4 g/liter solution of bone glue, 15-20 A/ft^2). In neither case was the plating good enough for superconducting application: both cavities were somewhat mishandled and were a little distorted (which, however, helped TE_{011}-TM_{111} mode separation). The cavity Q_o's were found to be of the order 6×10^6 and 10^7 at 4.2°K, with only an improvement of the order 2 at 1.85°K. (These numbers are to be compared with $Q_o = 7 \times 10^4$ for copper at 300°K.) Neither cavity was magnetically shielded; both cavities leaked on cool-down at the indium gaskets, particularly at the λ-point of helium.

Because of the above difficulties, we have now established our own plating shop. The two cavities above have been replated, again at 15 A/ft^2, 0.001 in. thick, and retested. Magnetic shielding has been used in the form of a μ-metal can 0.040 in. thick. New values of Q_o have been 8×10^7 and 4×10^8 at 2°K, respectively, i.e. with I's approaching 10^4. Several new S-band cavities have been prepared and are being tested. With these, experiments can be done more quickly to check plating parameters, e.g. current density (which may well come down to the 2.5 A/ft^2 commonly used in U.S. laboratories) and glue concentrations. Certainly the small quantity of bone glue at present used gives a much smoother surface than with no glue at all. Some conditioning of the copper substrate is being done (e.g. vacuum or reducing-gas furnacing) to produce epitaxis of lead.

Tests are also being done on model structures to investigate field patterns, check R/Q values and develop coupling systems. Other tests are being done to develop components for the rf system. The system envisaged is "conventional" for a superconducting system, but major use is being made of strip-line and solid-state devices. Future work will be aimed at "high power" models to check out limiting E-field values for the HEM_{11} deflecting wave in π mode; after this the real deflecting cavities will be built.

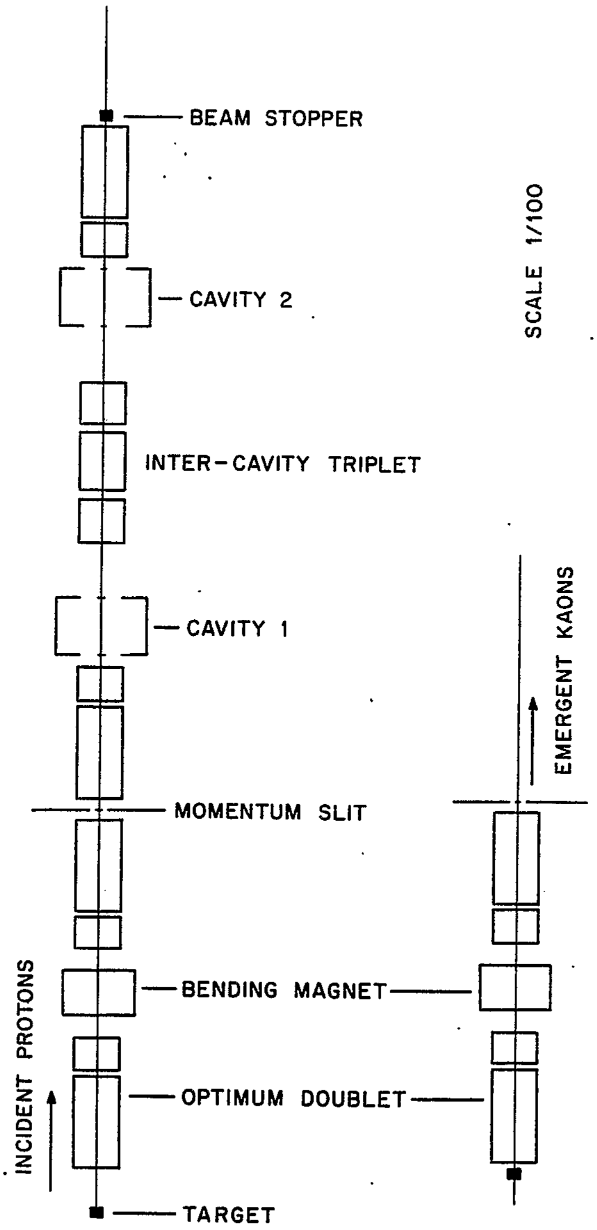

Fig. 1. Rf separated beam.