HIGH FIELD TESTS IN A MODEL SUPERCONDUCTING RF SEPARATOR AT 1.3 GHz

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Abstract

Superconducting RF separators proposed at the Rutherford Laboratory are planned to operate up to a maximum mean deflecting field $E_o = 3.6$ MV/m. Tests have been carried out on a 2-cell full scale model (with lead plated on a copper substrate) to prove the structure can operate at or near the design fields. Fields up to $E_o = 2.12$ MV/m, corresponding to 2.74 MV/m on the design structure, have been obtained.

1. Introduction

It is well known that at high momenta RF separators give a greater yield of wanted particles than the electrostatic type. Even at the momenta of Nimrod secondary beams, significant increases in yield are obtainable[1]. In addition to the more usual application to bubble chamber beams, RF separators may be used in counter beams. However, the long pulse lengths and high duty cycle (eg. 500 ms pulses, 25% duty cycle) require the RF separators to be superconducting.

A feasibility study of superconducting RF separators has been undertaken at the Rutherford Laboratory, as has also been done at other laboratories, notably Brookhaven and Karlsruhe. The study at the Rutherford Laboratory has been based on lead as the superconducting surface (electro-deposited onto a copper substrate) on the grounds of relatively easy technology and cost; and proposed RF separators have been designed with a geometry and field levels to match the capabilities of lead.

Proposed superconducting RF separators at the Rutherford Laboratory have a maximum mean deflecting field $E_o = 3.6$ MV/m, for which the peak magnetic and electric fields at the surface are 540 G, and 13.8 MV/m. A test programme has been carried out on a full-scale 2-cell model to prove that the structure can operate at or near these design fields. It is the purpose of this paper to describe some of the details of the processing and results of the tests.

2. Model Structure

The proposed separator cavities will be 10 cells long, and operate in the uniform periodic π-mode, with $V_{ph} = c$. The disc thickness has been chosen to be $t = 3.95$ cm ($t/\lambda = 0.1711$) specifically to reduce the peak fields at the surface. The test structure has a disc thickness $t = 2.196$ cm (chosen for historical reasons), but the design surface fields can be obtained by operating at a mean deflecting field up to $E_o = 2.795$ MV/m.

The test model is shown in Figure 1, and consists of two cells plus two end terminations and 'beam pipes', to simulate a realistic section of a full scale RF separator cavity. The end terminations were half-cell sections lengthened to remove reactive loading due to the beam pipes. The resulting field perturbations gave two effects to be taken into account in evaluating the measurements of Section 5: compared with the equivalent section of infinite structure the Q-value is reduced by 10%, and the mean deflecting field at the cavity centre is 6.7% greater.

3. Plating

The copper cavity was made one-piece by electro-forming the outer cylinder onto OFHC copper discs. This was done to remove the problem of RF joints, where previous experiences with jointed test models were largely unsuccessful. For manufacturing reasons the corners between discs and outer cylinder had 45°, 0.4 cm chamfers rather than radiused corners preferred for lead plating. In practice, difficulty was experienced in getting good lead plating at the chamfers and the lead deposit was always thinnest there. Nevertheless, the advantage of having a jointless structure outweighed this difficulty.

The anodes themselves were made of 6 N's lead (ie. 99.9999% pure), shaped to follow (approximately) equipotential surfaces, and were bagged in fine-weave crimplene to avoid sedimentation. Three anodes per cell were used, a total of nine in all. Prior to the plating process the cavity was mechanically polished (it was considered the risk of embedding polishing material in the copper was less than the effects of etching due to repeating chemical cleaning). The plating process itself was essentially a standard commercial process with some modifications: Double the standard quantity of bone glue was used. After flashing, the peak plating current was 5.38×10^{-3} A/cm^2, and a mean thickness of 1.27×10^{-3} cm of lead was deposited. All metal not to be plated was protected from the plating solution. The plating was done with the cavity axis vertical (anodes rotating, cavity fixed) or horizontal (anodes fixed, cavity rotating), but there was no clear advantage either way. At no stage was the cavity allowed to dry in the atmosphere. Anode disassembly and final washing were done in a deep bath with de-oxygenated water. Removal of water was done in acetone in a stainless steel tank which was then evacuated for the final drying. A total of four successful platings were done, each requiring on average four attempts. After the RF tests the lead was chemically analysed, and the results will be discussed in Section 5.

After assembly the model was vacuum-baked for some 48 hours at 100-110°C, after which the pressure was typically 5×10^{-7} torr, falling to 1×10^{-7} torr at room temperature. In its cryostat, the assembly was cooled slowly, using nitrogen gas only (obtained by boiling liquid nitrogen in the bottom of the

*Visitor from the Argonne National Laboratory, USA cryostat) to minimise mechanical strain to the lead and joints. Further cooling with helium gas was done with the gas blown uniformly over the length of the model. Care was taken to minimise the temperature gradient across the cavity at the critical temperature of lead to reduce the risk of thermoelectric currents, and typical temperature differences a little less than 0.1°K were obtained. At 4.2°K, low power (ie. few milliwatts) measurements of Q-value were taken.

4. Measurements

The RF system is shown in Figure 2. The RF source was a power oscillator phase-locked to a frequency synchroniser. Difficulties were experienced in feeding the cavity through the amplitude switch, so two alternative methods were used.

a. Transmission method

In this method both loops were used to determine coupling constants to the cavity, and the measurements were taken under CW conditions. Through each loop in turn forward, reverse and transmitted power were measured, with the drive frequency on and off resonance. Decay curves were found for each sense of excitation, from which the appropriate loaded Q-values were deduced. The cable loss factors can be found from the readings taken off-resonance, since all the forward power to the cavity is reflected.

$$\eta = (P_r'/P_f')^{\frac{1}{2}}$$, where P_r' is the measured reflected power, off-resonance; P_f' is the measured forward power, off-resonance (4i)

On resonance, the power coupled to the cavity is

$$P_c = \eta_s \, P_f(s) - P_r(s)/\eta_s - P_t(q)/\eta_q \qquad (4ii)$$

Where s = 1,2, q = 2,1 refer to the driven loop, and P_c, P_f, P_r, P_t are cavity, forward, reverse and transmitted power respectively. The coupling constants are $\beta_s = P_t(s)/\eta_s \, P_c(q)$, and the unloaded Q-value, Q_o is given by

$$Q_o = Q_L \, (1 + \beta_1 + \beta_2) \qquad (4iii)$$

(It is to be noted that coupling losses are lumped into cavity losses, so that calculated values are somewhat pessimistic). Corresponding field values can then be computed from

$$E_o = 0.471 \, (P_c Q_o)^{\frac{1}{2}} \text{ MV/m (with } Q_o \text{ in units of } 10^8);$$
$$E_p = 4.68 \, E_o; \quad H_p = 193 \text{ gauss/MV/m} \qquad (4iv)$$

where in the calculated value for E_o field perturbation has been included.

The transmission method has two shortcomings, both of which affect the accuracy of the measurements. Firstly, if the field levels in the cavity are not identical for excitation on the two loops, there will be an error in the computed value of β, if Q_o is a function of power level. Secondly, β can change if the loop distorts under high power operation. In fact, both of these effects occurred, so to avoid gross inaccuracy the following technique was employed. One loop (β_2) was operated in a decoupled state, and left unchanged. To avoid distortion this loop was excited at low power only. The value of β_2 could be measured at low and high power, which indicates the change in Q_o. The low power value of Q_o could be determined from equation (4iii) and the measured value of β_1. The power coupled into the cavity could be measured with reasonable accuracy, which gave sufficient information to calculate the high field values for the cavity. Despite this technique, complete consistency was not obtained in the various computations of β_1. Despite much study, the reasons for this are not fully understood, but to some degree are due to loop distortion, and that the measurements were made under different dynamical conditions.

b. Emitted Power Measurement

In this method only one loop carries high power, the second is always decoupled and is used as a calibrated detector only. Power to the first loop can be switched in amplitude (but practical difficulties prevented this); or effectively switched by a rapid change in drive frequency so that all the forward power is reflected. Forward and reflected power are measured, on and off resonance; also note is made of the transmitted signal. When the forward signal is driven off-resonance, it is completely reflected, also the cavity emits power. The total reflected signal is the vector sum of the emitted wave at the cavity resonant frequency, and a reflected wave removed many bandwidths in frequency. From a detector previously calibrated for this type of FM response, the power can be deduced at the instant the cavity emits, and this automatically takes into account the instantaneous value of β, and the condition of the loop. Thus the limitations of the previous method are avoided, even though the loop is working in effect CW. Loss factors are measured off-resonance, as before. Cavity power is given similarly as before.

$$P_c = \eta P_f - P_r/\eta \qquad (4v)$$

and $\beta = P_e/\eta \, P_c$, where P_e is the instantaneous emitted power (4vi)

Small corrections due to transmitted signal are ignored, since β_2 is of the order 0.02. The loaded Q-value is deduced from decay, so the Q_o-value and fields can be computed from equation (4iv).

5. Results and Discussion

The figures contained in Tables 1 and 2 are results obtained from the last of four successful platings. In previous runs Q_o values were very similar, but vacuum difficulties and gross loop distortion limited high power operation. Even for the measurements reported here, there were vacuum difficulties and the high power measurements were made at 2.05°K (below which the cavity leaked). The several vacuum difficulties give an indication of the tolerance of lead to contamination by vacuum

P_c Watts	$Q_o \times 10^8$	E_o MV/m	H_p Gauss	P_t/P_c mW/W	H_p^2/P_t $(\text{gauss})^2$/mW
0.0135	5.60	0.130	25	58.7	927
0.224	2.78	0.372	72	35.9	770
2.00	2.39	1.03	199	24.8	719
2.25	2.45	1.105	213	25.8	945
2.80	2.29	1.193	231	24.0	947
3.00	2.38	1.26	243	24.8	945
2.55	2.33	1.15	222	24.3	947

Table 1: Summary of results by Transmission Method

3.42	2.33	1.34	259	25.0	787
3.44	2.79	1.46	282	24.9	932
3.44	2.99	1.55	299	24.7	1008
3.80	2.40	1.38	266	22.1	844
4.0	2.28	1.42	274	22.5	835
4.92	2.36	1.61	310	20.9	935
5.74	2.07	1.62	313	20.3	843
7.32	1.98	1.79	345	17.3	938
8.18	1.87	1.89	364	16.6	928
9.50	1.88	1.99	384	15.7	990
		2.12	410		930

Table 2: Summary of results by Instantaneous Emitted Power Method

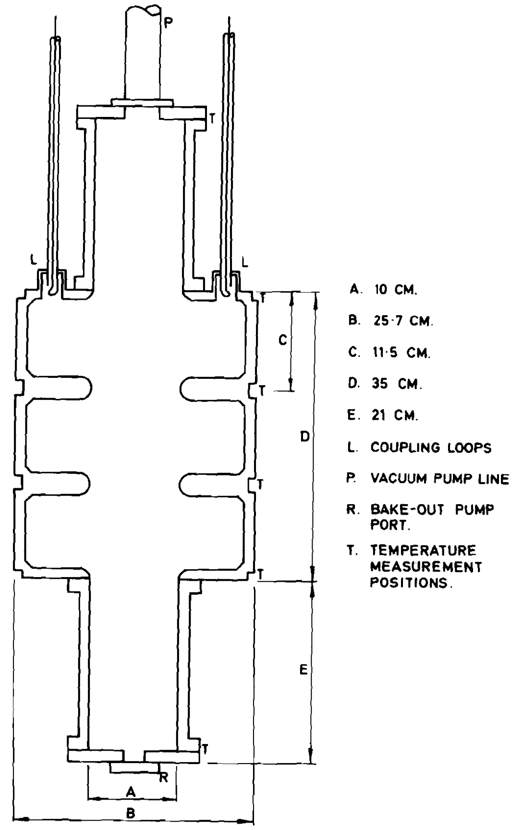

FIG. 1 SUPERCONDUCTING R.F. SEPARATOR 1·3 GHz TEST MODEL.

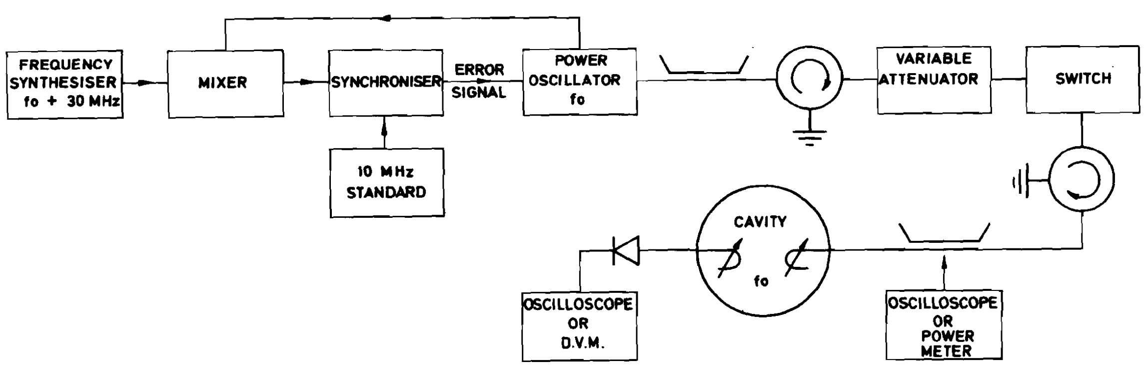

FIG. 2 R.F. SYSTEM

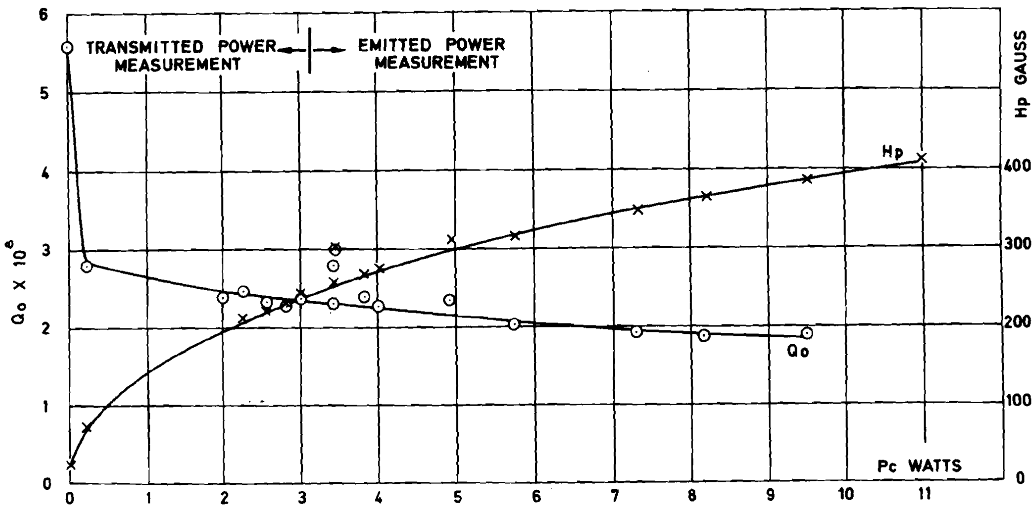

FIG. 3. COMBINED RESULTS : UNLOADED Q AND PEAK SURFACE MAGNETIC FIELD AGAINST CAVITY POWER

leaks and mechanical straining due to repeated temperature cycling: a vacuum leak requiring warm-up and repair will give a reduction in Q of the order of 30%, so that at least one 'accident' could be tolerated before major repairs involving replating became necessary.

At 4.2°K the unloaded Q-value was 1.64×10^{8}, ie. 84.8% of theoretical Q for a terminated structure. On cooldown to 2.05°K, the Q_o was 5.6×10^{8}, a further improvement of a factor 3.4 instead of the theoretical increase 37.5. Subsequent to the tests, the lead was analysed and found to contain 0.4% copper, 0.015% iron, 0.084% zinc. These impurities are much greater than intended, and account largely for the limited value of Q-improvement.

In the high field tests, both methods of Section 4 were used, with the highest fields being seen with the emitted power measurement. The results, given in the tables, are also collected in Figures 3 and 4. With increasing field the unloaded Q-value fell from 5.6×10^{8} to just under 2×10^{8}. For the model as a whole, the effective surface resistance degradation factor $\alpha^{2)}$ is 1.83. For fields $E_o \geqslant 1.5$ MV/m some signs of field emission were seen: i) periodic

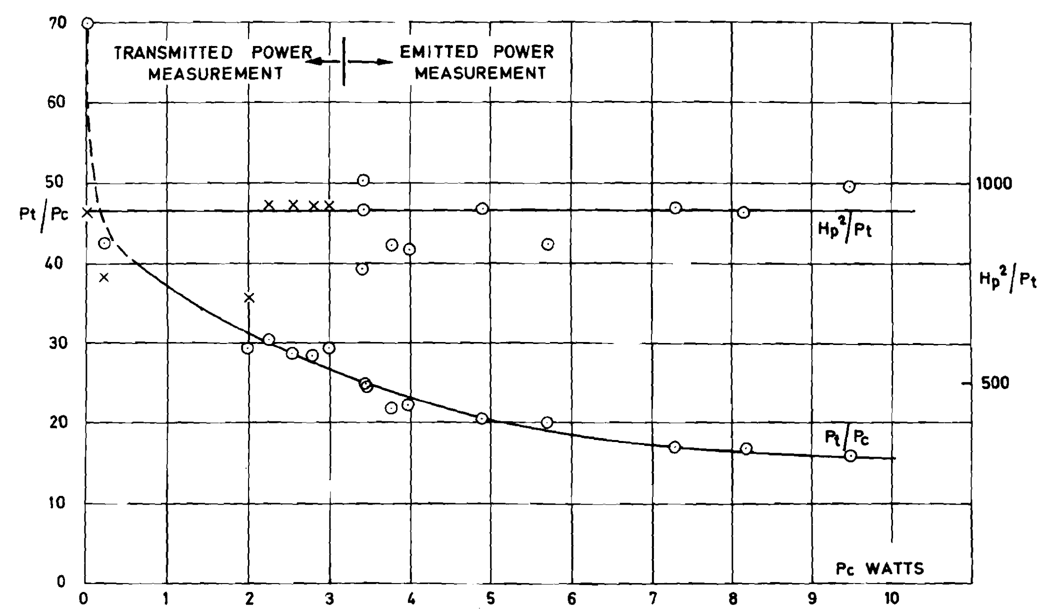

FIG. 4. COMBINED RESULTS H_p^2/P_t AND P_t/P_c AGAINST CAVITY POWER.

increases in vacuum pressure associated with the input of RF power, ii) X-ray emission, measured at the mid-plane of the cavity, and some 40 cm distance. The X-ray emission was in the range 0-6 mR/hr (with one short burst to 14 mR/hr), and was not correlated with power level, and always reduced after some minutes of running, ie. conditioning was taking place. (On subsequent dismantling of the cavity, no signs of surface damage could be seen, so it was not clear whether gas discharge or field emission was the source of radiation). The highest field run was 410 gauss (E_o = 2.12 MV/m), which would exist for some 40-50 ms (of 200 ms pulses) before clamping occurred due to the above effects. To the first order additional losses due to electron loading can be accounted for, and the cavity field still computed.

The curves in Figures 3 and 4 were computed with values of β obtained as in equations (4iii) and (4vi), and in themselves show good agreement. Other computations of β depending on the ratio of reflected power, or cavity power to incident power were much less consistent (and more optimistic). A study of the errors due to the measurement of individual parameters, and tuning of cavity resonance, all gave results well within the scatter of computed β values. Errors in coupling losses do not account for the scatter either, since it can be seen from Figure 4 that the ratio of H_p^2/P_t is constant. In lumping the coupling losses with cavity losses the results of Figure 3 are somewhat pessimistic.

Despite the practical difficulties associated with this model, of difficult geometry for plating, chemical contamination, and poor vacuum, high surface fields have been achieved. The maximum field seen was 410 gauss, corresponding to 2.74 MV/m on a full-scale structure. The experience gained has suggested several detailed improvements to be made in the processing which should lead to even better results. It is now planned to build a full-scale operational separator cavity in its cryostat for completion early in 1972 after which a complete RF separator system could be built.

Acknowledgements

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References

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DISCUSSION

M. KUNTZE : What was the limitation on the 410 G ? Did you observe multipactoring levels at low fields in your measurements ?

A. CARNE : There were instrumental difficulties, both in the main coupling loop and in clamping of the r.f. source. For fields above E_o = 1.5 MV/m there was some X-radiation, also frequency clamping indicating electron loading. Subsequently the cavity was dismantled, but no sign of surface damage was seen, so it was not clear whether the source of radiation was gas discharge or field emission. We did not observe multipactoring at low fields.

P.B. WILSON : What was the peak electric field present at the surface of your cavity at the 400 G peak magnetic field level ?

A. CARNE : For the model E_p/E_o = 4.68, so that at the maximum mean deflecting field achieved of 2.12 MV/m, E_p = 9.92 MV/m.