SUPERCONDUCTING LINACS

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At the Rutherford Laboratory the design of a superconducting proton linear accelerator has been considered*. This machine (Planet) would accelerate a proton beam of the order of 1 ma in cw operation. The rf power lost to the accelerating structure would be reduced by a factor of approximately 10^4 by supercooling, as compared with conventional linacs.

The rf power lost to the beam becomes now considerably greater than that lost to the structure, where, typically, a 1 ma proton beam in a 20 Mev cavity at frequency 200 Mc/s absorbs approximately 20 kw as compared with 26 watts lost to the structure. This machine would be a multi-tank structure. Some of the problems involved in this linac are enumerated below:

1) Phasing problems.
2) Beam loading. This has been studied by A. Carne.
3) Quadrupole design, alignment errors, etc.
4) Beam dynamics.
5) Rf structures.
6) Feeding cold tanks with rf, frequency control, servo control of phase and rf power levels.
7) Mechanical problems, as there are heat insulation, vibration, refrigeration, shrinkage, alignment, plating of structures, etc.
8) Properties of superconducting materials, consequence of multipactoring and local heating, x ray radiation, etc. This has been considered by A.P. Banford.
9) Nuclear physics to be done with this machine.

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*A.P. Banford and G.H. Stafford, "The Feasibility of a Superconducting Proton Linear Accelerator", NIRL/R/7, 1961

In parallel with work on Planet, there is a computational study being carried out on a pulsed linac injector for a possible 300 Bev proton synchrotron. Both machines will consist of a series of separated tanks, so that the problems of particle motion versus tank rf field, tank or intertank phase, intertank focusing, etc., are similar, and the outstanding difference between the two machines are that of prohibiting particle losses in the Planet machine and the transient effects of beam loading in the pulsed machine. In the preliminary study on the pulsed linac beam loading effects are being ignored (it is assumed that resistive loading can be controlled by a fast field amplitude control, and that reactive loading can be tuned out), so that many results are applicable to both machines.

Both machines may be divided into two sections: below 200 Mev and above 200 Mev. Below 200 Mev, the Alvarez waveguide has good efficiency (i.e. good shunt impedance), but above 200 Mev the Alvarez structure becomes inefficient and must be replaced by a traveling wave system. In practice the tanks would be operated in the resonant π-mode, where field and phase may be treated as lumped effects and may be controlled by single devices. For example, a single frequency tuner would suffice for a resonant tank, but for a traveling wave tank the tuner would have to act smoothly over the whole length of the waveguide to prevent phase change between beam and wave, and also to avoid reflections in power transmitted along the waveguide.

A comparison of resistive losses in the conventional type linac and the superconducting linac is given in Table 1. A preliminary estimate of costs for the Planet structure is tabulated in Table 2. Subsequent to this A.P. Banford studied cost figures as a function of frequency in the structure following the 50 Mev section. The following equation referring to a temperature of 4.2°K was obtained:

TABLE I

	200 mc/s throughout			200 Mc/s up to 50 MeV 400 Mc/s thereafter		
	section length (ft)	resistive losses to structure		section length (ft)	resistive losses to structure	
section		copper 40 °C	lead 4·2 °K		copper 40 °C	lead 4·2 °K
a) 0·5 – 50 MeV (alvarez)	100	3·4 mW	68 W	100	3·4 mW	66 W
b) 50 – 150 MeV (alvarez)	200	15·5 mW	311 W	140	15·5 mW	904 W
c) 150 – 600 MeV (π-mode)	910	67 4 mW	1350 W	640	67 4 mW	3900 W
d) 600 – 1500 MeV (t. w.)	1820	81 0 mW	1600 W	1285	81 0 mW	4700 W
totals						
final energy a) 50 MeV	100	3·4 mW	68 W	100	3·4 mW	68 W
b) 150 MeV	300	18·9 mW	379 W	240	18·9 mW	972 W
c) 600 MeV	1210	86·3 mW	1729 W	880	86·3 mW	4872 W
d) 1500 MeV	3030	167·0 mW	3329 W	2165	167·0 mW	9572 W

accelerating rates 1·7 mev/metre (200 mc s) 2·3 mev/metre (400 mc s)

TABLE 2

summary of costs

energy mev	refrigeration cost £m.	liquid N_2 £m	vacuum plant £m.	r. f. equipment £m.	vac vessel, liner, drift tubes, etc. £m	total £millions
0 - 50	0·090	0·010	0·030	0·050	0·300	0·480
50—150	0·215	0·020	0·070	0·100	0·600	1·005
150—600	0·530	0·050	0·300	0·200	2·500	3·580
600—1500	0·580	0·050	0·500	0·200	3·000	4·330

$$Z = \frac{\text{cost}}{\text{cost at 200 Mc/s}} = 0.15\ (f/200)^{a} + 0.145\ (f/200)^{-3/2} + 0.055 + 0.65\ (f/200)^{1}$$

where a = cost of refrigeration plant

b = cost of accelerating structure .

The first term on the right hand side in this equation refers to refrigeration cost. This is a function of rf power losses which have to be handled by the refrigeration plant. A cost estimate for the refrigeration plant suggests that this is proportional to $(\text{power})^{0.6}$, although a more practical estimate might be $(\text{power})^{1}$. Taking the rf losses proportional to f^{2} (assuming an acceleration rate proportional to f) result in possible values for a of 1.2 and 2. The second term is related to the liquid nitrogen plant and cost of vacuum parts. The third term refers to cost of the rf system, which is assumed to be constant because essentially all of the power is absorbed by the beam. The fourth term is the cost of the accelerating structure, which is assumed to be proportional to the surface area to be machined, hence $b = -3/2$. Values of $b = -2$ and $b = -1$ have been considered.

A plot of Z versus frequency for the various parameter values is shown in Fig. 1, from which it is concluded that 400 Mc/s is near the economic optimum operating frequency.

The question of beam loading in the Alvarez structure section of Planet has been considered by A. Carne*. In short, the conclusions are that the resultant phase error is given by $\tan \Psi = \frac{1}{2} \tan \phi_s$ for a matched system, e.g. for a phase stable angle $\phi_s = 30^{\circ}$, the maximum phase change is of the order of 16°. Fluctuations of the order of 10% in beam intensity produce a mean phase error of $<< 1^{\circ}$. These effects can be corrected by known tuning devices, namely slow tank autotuning systems and reactance tubes for fast control.

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*NIRL/M/34, to be published shortly

Measurements on superconducting materials were done by A.P. Banford. The specimens used form quarter-wavelength twin lines shorted at one end and the surface resistivities are derived from the measurement of the Q value at 400 Mc/s.

The specimens are 36 cm long and are bent into hairpins 18 cm long with the legs separated by about 9 mm. These are made of wire 1-1.5 mm diameter if the material is available in this form; if not, rectangular cross section specimens are cut from a sheet. The samples are hung centrally inside a lead-lined helium container, as shown in Fig. 2, by means of a 0.025 mm diameter nylon thread attached to a perspex rod. Coupling is done by means of two loops and can be varied by raising or lowering the specimen by means of the perspex rod. In the liquid helium region, this varies the penetration of the hairpin into the liquid, but this appears to have no effect apart from a slight change of resonant frequency due to the dielectric constant of the liquid.

The reference standards are made from electropolished copper wire and the Q values are measured at room temperature by measuring the frequency response. A block diagram is given in Fig. 3. Q values obtained are of the order of 1000 and are close to the theoretical values. The shield is responsible for only 1/800 of the total resistive losses if it has the same resistivity as the hairpin. Dielectric losses in the nylon threads have been calculated, and are negligible even when the hairpin is superconducting. This is because the threads are very thin and are located near the minimum of the electric field. The sensitivity of the equipment is such that it is possible to decouple the specimen far enough to measure directly an almost unloaded Q. Under these conditions the top of the hairpin is about 2 - 3 cm below the loops and the transmission coefficient is at least 50 db.

At liquid helium temperature the Q values are obtained by measuring the time constant of the system indicated in Fig. 4. The oscillator is pulse modulated and the output from the crystal detector is observed on an oscilloscope. The crystal is "square-law" up to an output voltage of 10 mv. The oscilloscope has a long persistence screen, and the Y sensitivity used is 1 mv/cm. The time base is triggered by the back edge of the modulating pulse. The oscillator is not frequency-stabilized and the resonant frequency of the hairpins is altered by mechanical vibrations, so that with a high Q the system is on tune only for very short periods of time. However, provided that there is some energy stored when the input rf is cut off (in less than 1 μsec), the output signal will decay exponentially. Due to the frequency drifts, the amplitudes of successive decay curves differ greatly. This inconveniences the measurements a little, but all the decays have the same time constant which is computed from the decay half-life measured directly on the long persistence oscilloscope screen. The longest time constant yet measured is 590 μsec ($Q = 1.5 \times 10^6$) for an electropolished lead specimen of 99.99% purity. The results to date are summarized below:

Material	Purity	Impurities	State	Improvement Factor
Pb wire	99.8%	Traces of about 12 elements mainly Sb, Cu, Ag	"as it comes"	770
			electropolished	3450
Pb sheet	99.99%	Ag	"as it comes"	1400
			electropolished	4100
Nb wire	99.8%	Ta, Fe	"as it comes"	640
Pb-Bi eutectic	58% Bi 42% Pb	?	"as it comes"	50
Soft solder wire	50% Pb 50% Sn	?	"as it comes"	70
Pb electro-plated on Cu			with or without subsequent electo-polishing	3900 - 4500

All measurements were done at 4.2°K. The improvement factor is the ratio of the measured surface resistivity to that of room temperature copper and is expected to be 1.7×10^4 at 400 Mc/s for lead. It was possible to decouple the specimen to the point at which further decoupling did not increase the measured time constant. Under these conditions the top of the hairpin would be 6 - 8 cm below the loops. The electropolishing technique has been improved since the above measurements were made, and some electroplated specimens are also ready for test. The intention is to measure the Q of the best of the hairpins at a number of temperatures and so evaluate the magnitude of the residual resistivity. Preliminary measurements show that the residual resistivity is about 55% of the total resistivity at 4.2°K.

The oscillator used has a maximum output of a few milliwatts, and the amount of power dissipated in the hairpin is even less. Preliminary measurements indicate power dissipations of the order of 100 μwatts at most. For the best superconducting hairpin this corresponds to a peak current of 1.2 amps, i.e. a magnetic field of about 3.5 gauss. Thus to achieve critical field levels, which is about 500 gauss for lead, a peak rf current is needed of 170 amps and a power dissipation of 2 watts. This will be attempted in the near future when a higher power oscillator-amplifier is available.

The best resistivity values so far are found to be a factor of 10 worse than expected. It is, of course, hoped to do better than this, but if this were to be the best that could be done, the cost of a 50 Mev Planet would be £7.3×10^5 instead of £5×10^5. This is because the helium refrigerator cost rises less than linearly with the power handled, and also because the refrigerator is not the most expensive component. It should also be borne in mind that although lower surface resistivities will lower the refrigerator cost, the expense of preparing the surfaces may become a significant extra item in the total cost.

Plans for the immediate future involve measurement of the effect of external magnetic fields, a repeat measurement with a cleaner Nb specimen and measurements of the same specimens at 1200 Mc/s to investigate frequency dependence of the residual resistivity.

Some measurements were also done with superconducting joints of niobium wire with a diameter of 0.45 mm. Compared with a measured critical current of 85 amps for a joint free sample, a value of 50 amps was obtained for an argon arc welded joint and 37 amps for the "best" mechanical joint.

Discussion

L.C. Teng (ANL): Have you tried any other materials? Sodium, for instance?

K. Batchelor (Rutherford): We have not tried anything other than mentioned here. Certainly other materials should be tried.

L. Smith (LRL): You do not consider that tin is a useful material?

K. Batchelor (Rutherford): We would prefer to work with something which has a rather higher transition temperature than tin. 4.2^{o}K is easier to obtain from the point of view of refrigerator costs and so on.

V.W. Hughes (Yale): Did you consider the problem of beam dynamics in connection with heating from stray particles?

K. Batchelor (Rutherford): This is quite a problem. We tend to approach this from the point of view that we would restrict the beam at the entrance to each cavity. We would tend to make apertures as large as possible.

K. Johnsen (CERN): Superconducting linacs have been considered at CERN by Lapostolle. The conclusion was that superconducting linacs, superconducting magnets, etc. are somewhat in the future. More basic research should be done first. A more immediate application could be a superconducting rf separator.

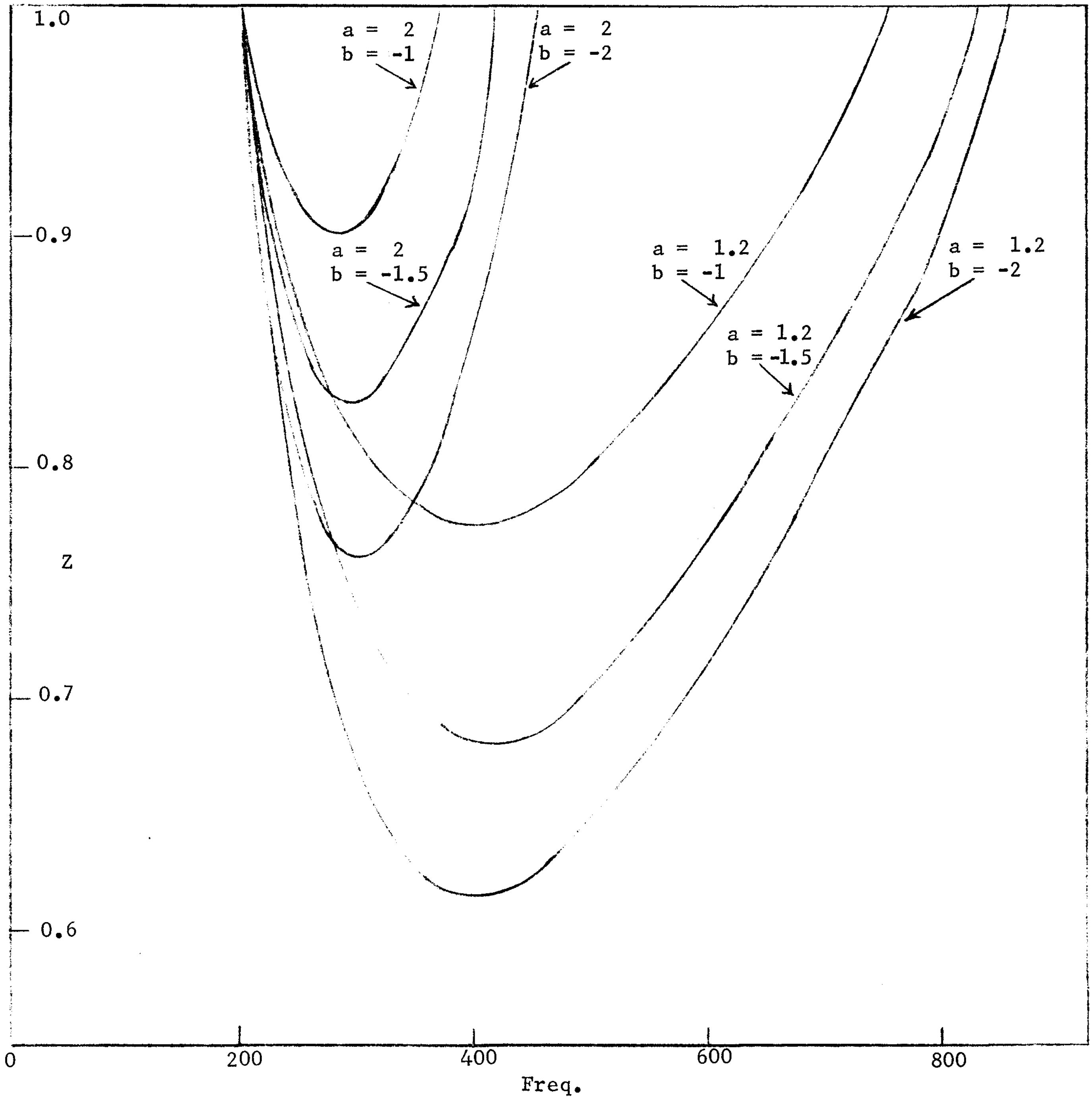
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Fig. 1

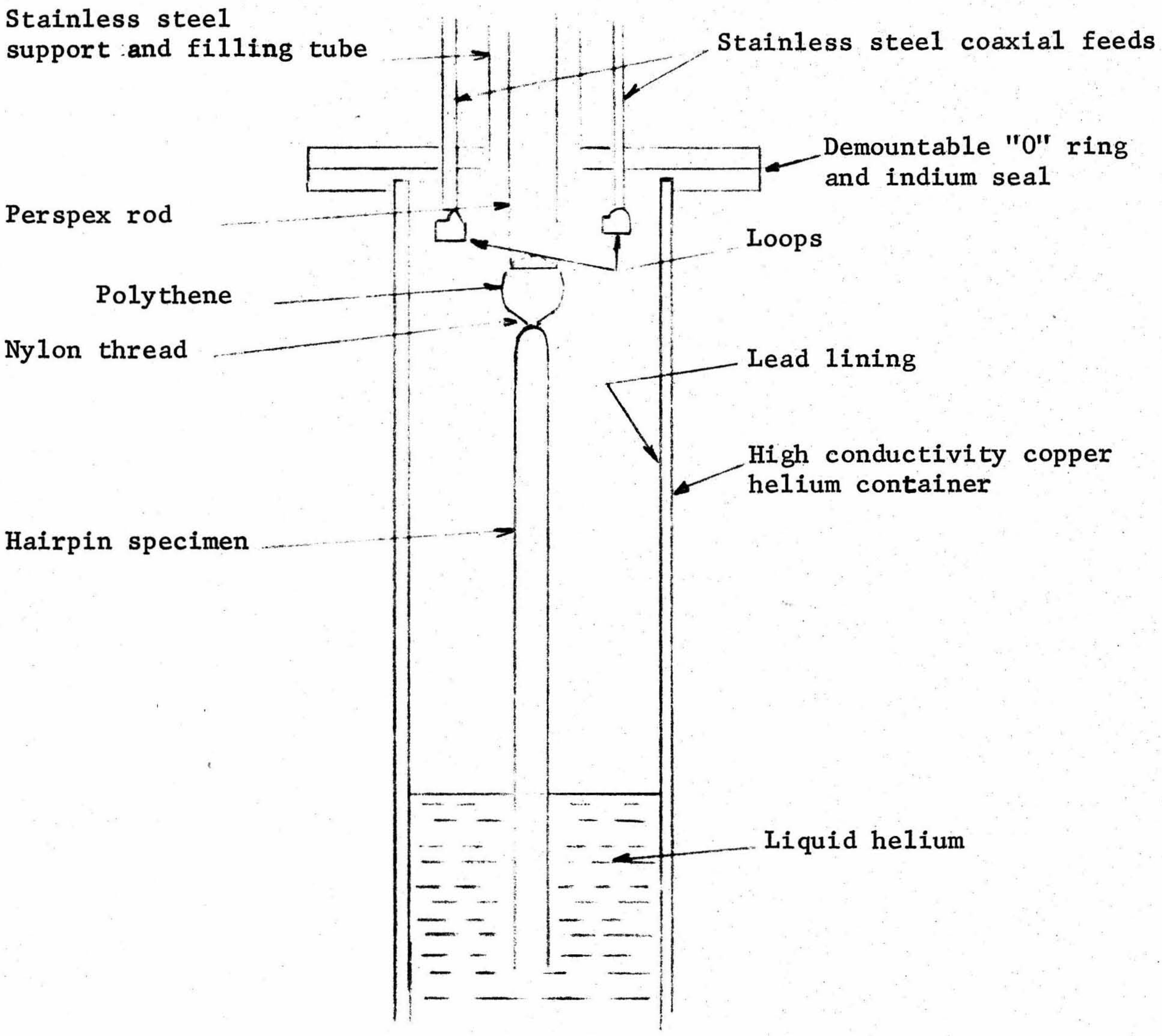

Fig. 2

Experimental arrangement

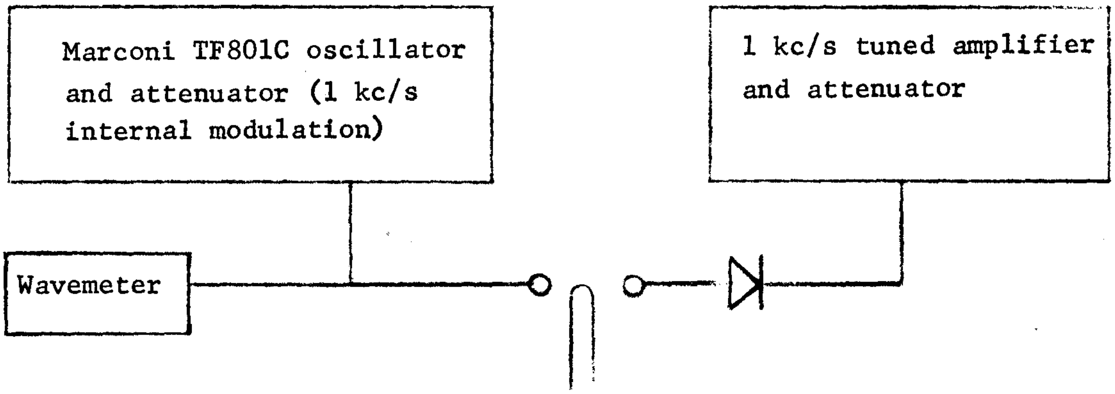

Fig. 3

Room temperature Q measurement

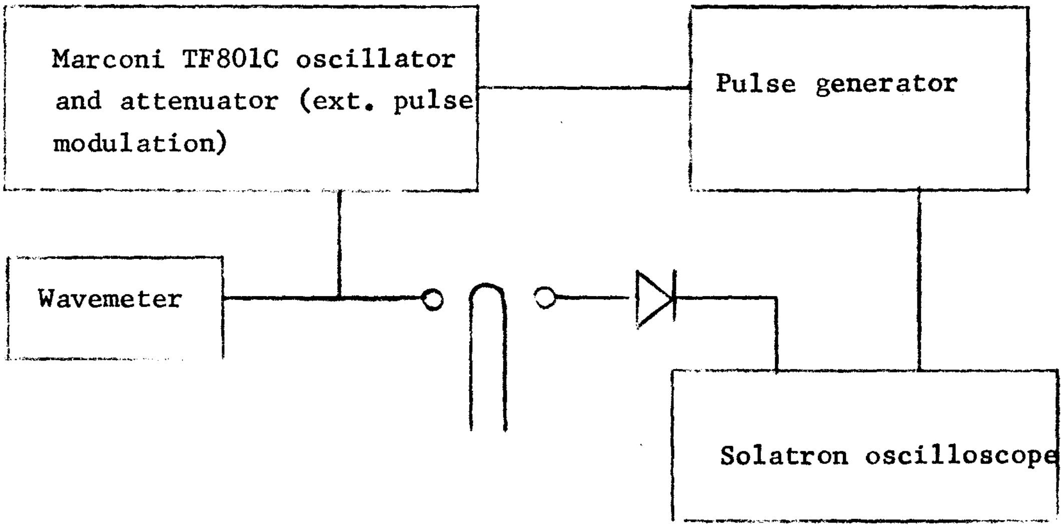

Fig. 4

Superconducting Q measurement