SUPERCONDUCTING LINACS

R. B. Neal
Stanford University

The Stanford group was originally interested in low temperature linear accelerators as a possible method of increasing the energy of the 1 Bev Mark III linac and also because this is a topic of intrinsic interest in itself which may have great potential impact upon the future of accelerator technology. Considering the facts that the energy gain per unit length is already high in the Mark III accelerator and that a substantial increase in total length of the accelerator is not possible, the use of low temperatures may therefore be the only means of significantly increasing the power efficiency. Cooling a copper cavity with liquid nitrogen (80° K) would improve the shunt impedance by a factor of 3. Cooling to liquid helium temperatures (4.2°K), the improvements in the Q value and shunt impedance per unit length are of the order of 6.

In the following, reference is made to the results on superconducting cavities at S-band frequencies obtained by P.B. Wilson (Stanford University). Most of these results have been reported at the CERN Instrumentation Conference, July, 1962. Since then, results have been obtained with superconducting cavities using higher rf power levels. Here, a short review will be given with special reference to the latest results obtained.

Test cavities, 14 inches long and 14 inches diameter, were used. Results were obtained with both tin and lead plating of the copper cavity walls. S-band frequencies (2856 Mc/s) were used for all the following results. The cavity was excited in the TE_{011} mode; in this case the E lines are circular around the axis eliminating current flow across junctions and losses on the end plates. It was also possible in the present case to excite the TM_{111} mode; this was rejected by using a reentrant structure.

Experiments were carried out for a range of temperatures, i.e., 1.75° K to 4.2° K, by variation of the pressure over the liquid He vessel.

The experimental setup is shown in Fig. 1. A block diagram is given in Fig. 2.

Consider now the Q of a loaded cavity:

$$Q_L = \omega\tau$$

where τ is the time of decay of the square wave envelope amplitude to the (1/e) value.

From this one calculates the unloaded Q value, Q_U.

$$Q_U = Q_L\ (1+\beta)$$

where β is the coupling coefficient.

A measurement of β and τ yields therefore the value of Q_U.

The magnetic field at the midpoint of the particular cavity and of the particular mode used in this experiment is given by

$$H_{gauss} = 3.5 \times 10^{-3} \sqrt{P_c Q_U}\ .$$

A comparison of theoretical values and experimental results is given in Fig. 3. Comparison is made with theory given by A. B. Pippard, (Advances in Electronics and Electron Physics VI, Academic Press, Inc., N.Y., 1954, pp. 1-45) using experimental constants obtained by Grebenkemper and Hagen (Phys. Rev. 86, p. 673, 1952).

The Q values obtained with a tin covered cavity are all below the values obtained with the lead cavity, over the temperature range investigated. Fig. 3 shows that Q values of the order of 2.10^8 can be obtained. This is 2.10^3 to 3.10^3 times Q_{copper} at 300^o K.

The above-mentioned results referred to input power levels of 3 watts. Recently, work has been carried out with higher power input values. This was done by including a 1 kw rf amplifier in the experimental setup. This will make it possible to go substantially above critical magnetic field values. The resultant experimental values indicate that with power levels of up to 25 w, the Q values remain high; above this a fall off in Q values is observed, while for values of approximately 100 w, the values of Q decrease quite drastically.

With $H_{gauss} = 3.5 \times 10^{-3} \sqrt{P_c Q_U}$ and assuming an input power level of 100 w and a Q value of 10^8, the magnetic field value obtained would be 350 gauss. This is of the same order as the magnetic field in the Stanford Mark III accelerator with 10 Mw peak power input to a section and a gradient of 10 Mev/meter. It is clear that the present experimental results at the higher power levels fall, up till now, somewhat short of design values. It is not believed that the 25 w level represents a fundamental limitation due to high fields in the cavity, but may be due to the presence of a small non-superconducting region in the cavity due to an imperfection incurred during fabrication and assembly. Appreciable improvement over present experimental results shoud be possible.

Future work will involve measurement of ultimate field values. Because at present the rf power is pulsed with consequent frequency variation during the rise time of the pulse, as a refinement in experimental technique, it is intended to use a cw signal with a microwave switch, because at present there is a frequency variation during the rise time of the rf pulse.

After further tests at higher power levels with the present cavity are completed, it is contemplated to conduct tests with a reproduction of a Mark III accelerator cavity.

In connection with refrigeration some concern exists about heating effects due to beams hitting cavity walls. Also, after the particle beam is turned off, all the power coupled into the cavity will be dissipated in the cavity walls with possible overload effects on the refrigeration system. It may be necessary to provide interlocks which would turn off the rf power when the beam disappears.

At present, some doubt exists as to the economy of a superconducting linac at S-band frequencies, as the following simple calculation indicates. Considering

$$P_{refr.}/P_{o\ \text{into cavity walls}} = \frac{T_2 - T_1}{T_1}\left(\frac{1}{\eta_{refr.}}\right)\frac{1}{\beta}$$

and taking

$\eta_{refr.} = 75\%$, $T_1 = 4^{\circ}$ K, $T_2 = 300^{\circ}$ K and the coupling coefficient $\beta \cong 10$

leads to

$$P_{refr.}/P_{o\ \text{into cavity walls}} \cong 10 \text{ in this particular case.}$$

The present line of investigations will be pursued, however, since results to date are quite promising, and also because of possible application for particle separators.

Discussion

G.K. Green (BNL): Are the power levels mentioned dissipation power levels?

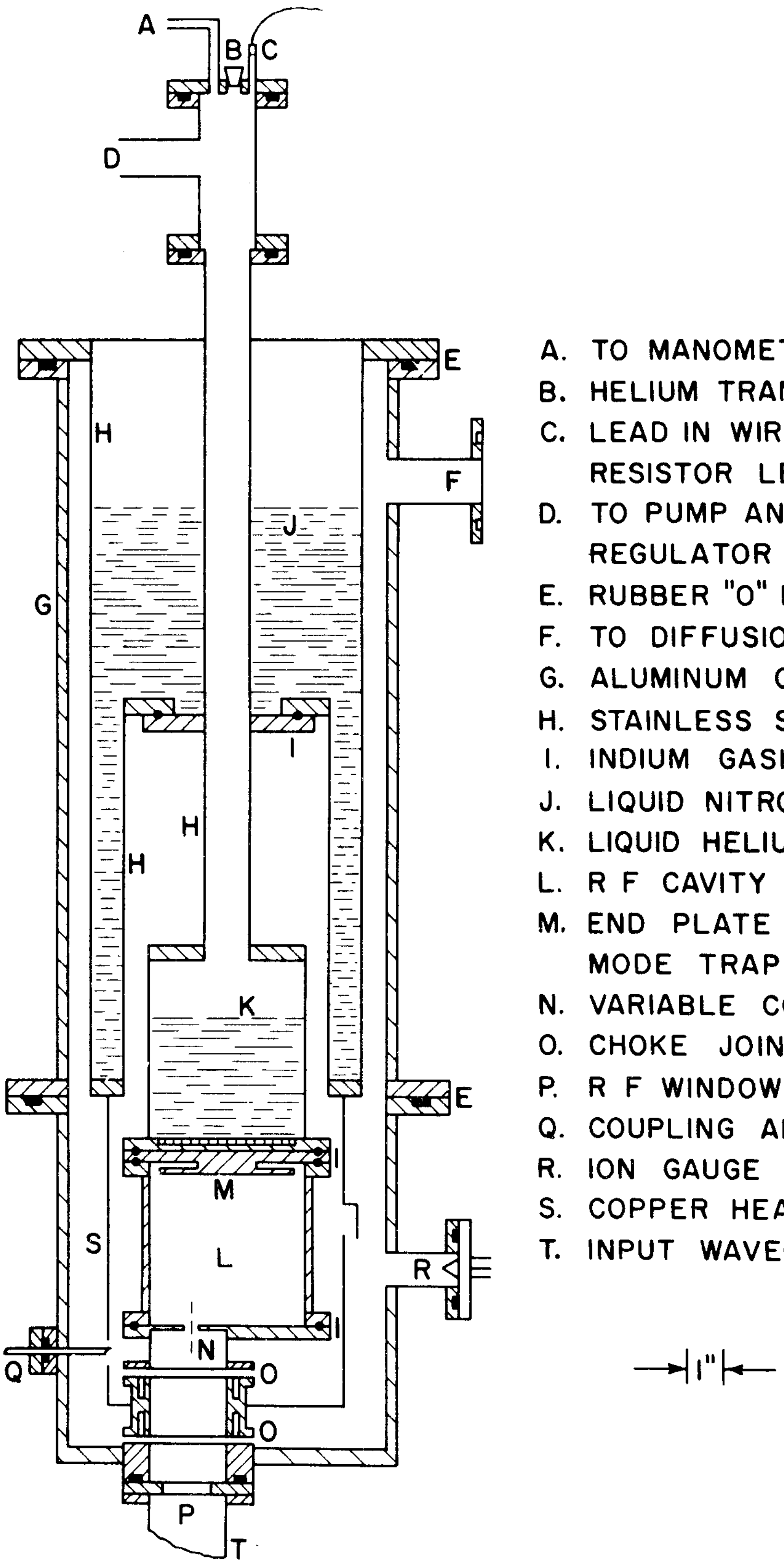
R.B. Neal (Stanford): No. These refer to peak pulse rf power levels.

G.K. Green (BNL): Is there a problem with cavity heating during the pulse?

R.B. Neal (Stanford): No. The pulse length is typically 75 millisec.

J.P. Blewett (BNL): Would the improvements obtained by going from 4°K to 2°K be worth the extra effort?

R.B. Neal (Stanford): This does not seem so. The main purpose of going to lower temperatures in this experiment was to obtain a more complete experimental curve. P.B. Wilson has the feeling that something like 3.5°K is about an optimum value. There does not seem to be any reason for using tin. Lead is certainly better from the point of view of higher Q value and higher critical temperature.



A. TO MANOMETER
B. HELIUM TRANSFER PORT
C. LEAD IN WIRES FOR
RESISTOR LEVEL GAUGE
D. TO PUMP AND PRESSURE
REGULATOR
E. RUBBER "O" RING GASKET
F. TO DIFFUSION PUMP
G. ALUMINUM OUTER WALL
H. STAINLESS STEEL TUBING
I. INDIUM GASKETS
J. LIQUID NITROGEN RESERVOIR
K. LIQUID HELIUM RESERVOIR
L. R F CAVITY
M. END PLATE WITH
MODE TRAP
N. VARIABLE COUPLING LOOP
O. CHOKE JOINT
P. R F WINDOW
Q. COUPLING ADJUSTMENT
R. ION GAUGE
S. COPPER HEAT SHIELD
T. INPUT WAVEGUIDE

Fig. 1

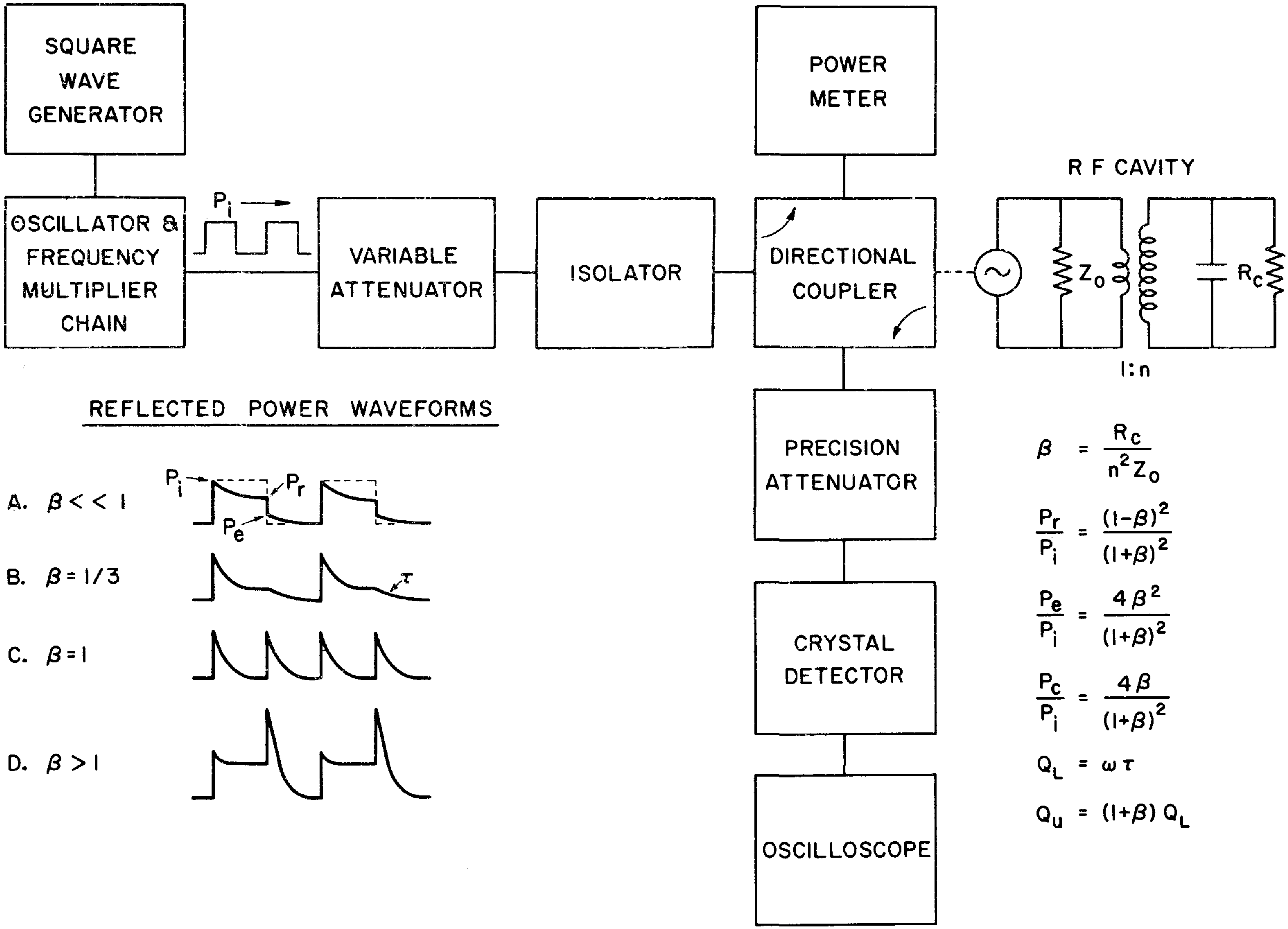

SQUARE WAVE GENERATOR
OSCILLATOR & FREQUENCY MULTIPLIER CHAIN
P_i
VARIABLE ATTENUATOR
ISOLATOR
POWER METER
DIRECTIONAL COUPLER
R F CAVITY
Z_o
R_c
1:n
PRECISION ATTENUATOR
CRYSTAL DETECTOR
OSCILLOSCOPE
REFLECTED POWER WAVEFORMS
A. $\beta << 1$
P_i
P_r
P_e
B. $\beta = 1/3$
τ
C. $\beta = 1$
D. $\beta > 1$
$\beta = \frac{R_c}{n^2 Z_o}$
$\frac{P_r}{P_i} = \frac{(1-\beta)^2}{(1+\beta)^2}$
$\frac{P_e}{P_i} = \frac{4\beta^2}{(1+\beta)^2}$
$\frac{P_c}{P_i} = \frac{4\beta}{(1+\beta)^2}$
$Q_L = \omega\tau$
$Q_u = (1+\beta) Q_L$

Fig. 2

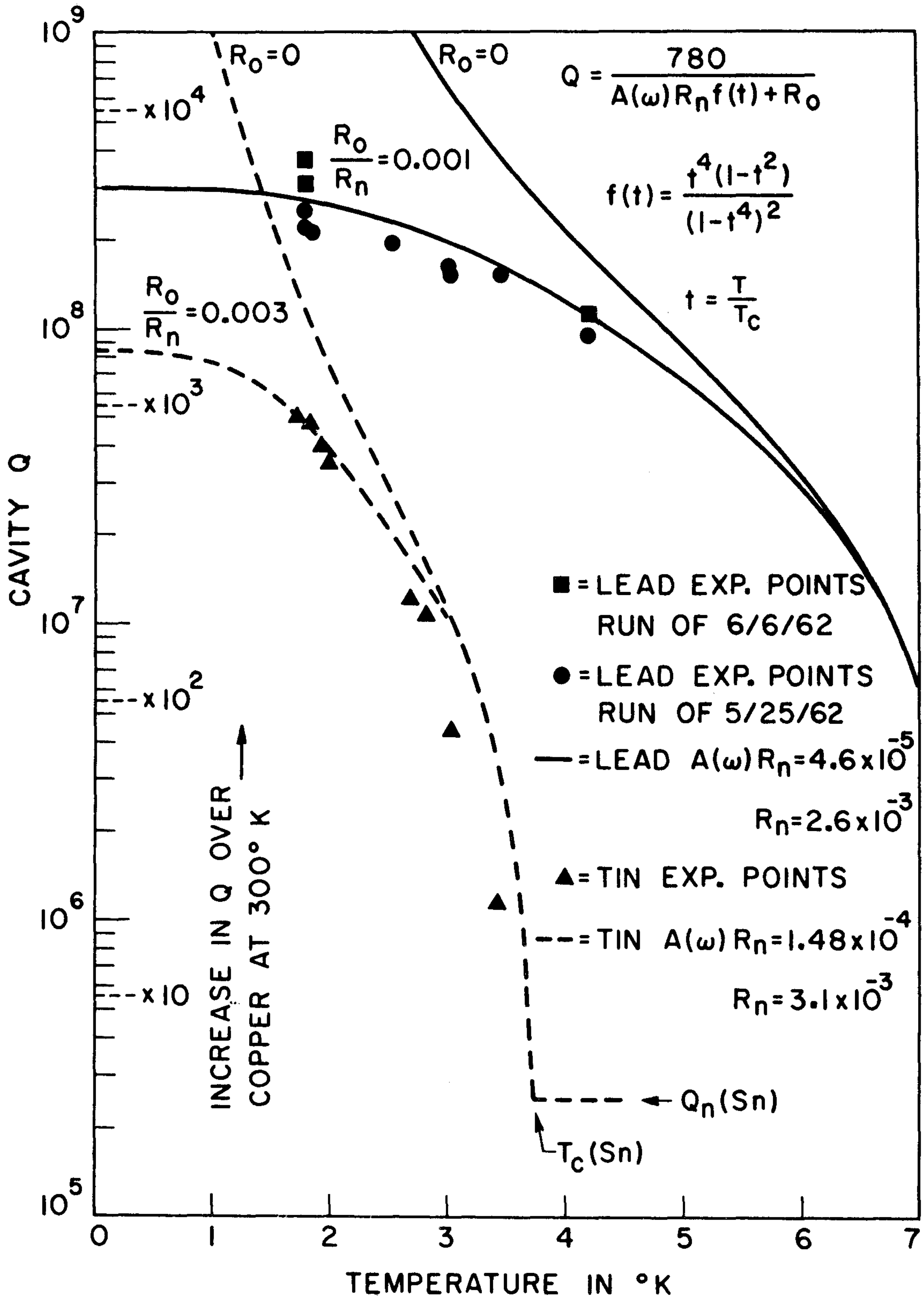

10^9
10^8
10^7
10^6
10^5
CAVITY Q
--x 10^4
--x 10^3
--x 10^2
--x 10
INCREASE IN Q OVER COPPER AT 300° K
$R_0=0$
$R_0=0$
$\frac{R_0}{R_n}=0.001$
$\frac{R_0}{R_n}=0.003$
$Q=\frac{780}{A(\omega)R_n f(t)+R_0}$
$f(t)=\frac{t^4(1-t^2)}{(1-t^4)^2}$
$t=\frac{T}{T_c}$
■ = LEAD EXP. POINTS RUN OF 6/6/62
● = LEAD EXP. POINTS RUN OF 5/25/62
— = LEAD $A(\omega)R_n=4.6\times10^{-5}$
$R_n=2.6\times10^{-3}$
▲ = TIN EXP. POINTS
--- = TIN $A(\omega)R_n=1.48\times10^{-4}$
$R_n=3.1\times10^{-3}$
$\leftarrow Q_n(Sn)$
$T_c(Sn)$
0
1
2
3
4
5
6
7
TEMPERATURE IN °K

Fig. 3