ISTITUTO NAZIONALE DI FISICA NUCLEARE - ISTITUTO NAZIONALE DI FISICA NUCLEARE - ISTITUTO NAZIONALE DI FISICA NUCLEARE - ISTITUTO NAZIONALE DI FISICA NUCLEARE - ISTITUTO NAZIONALE DI FISICA NUCLEARE - ISTITUTO NAZIONALE DI

Laboratori Nazionali di Frascati

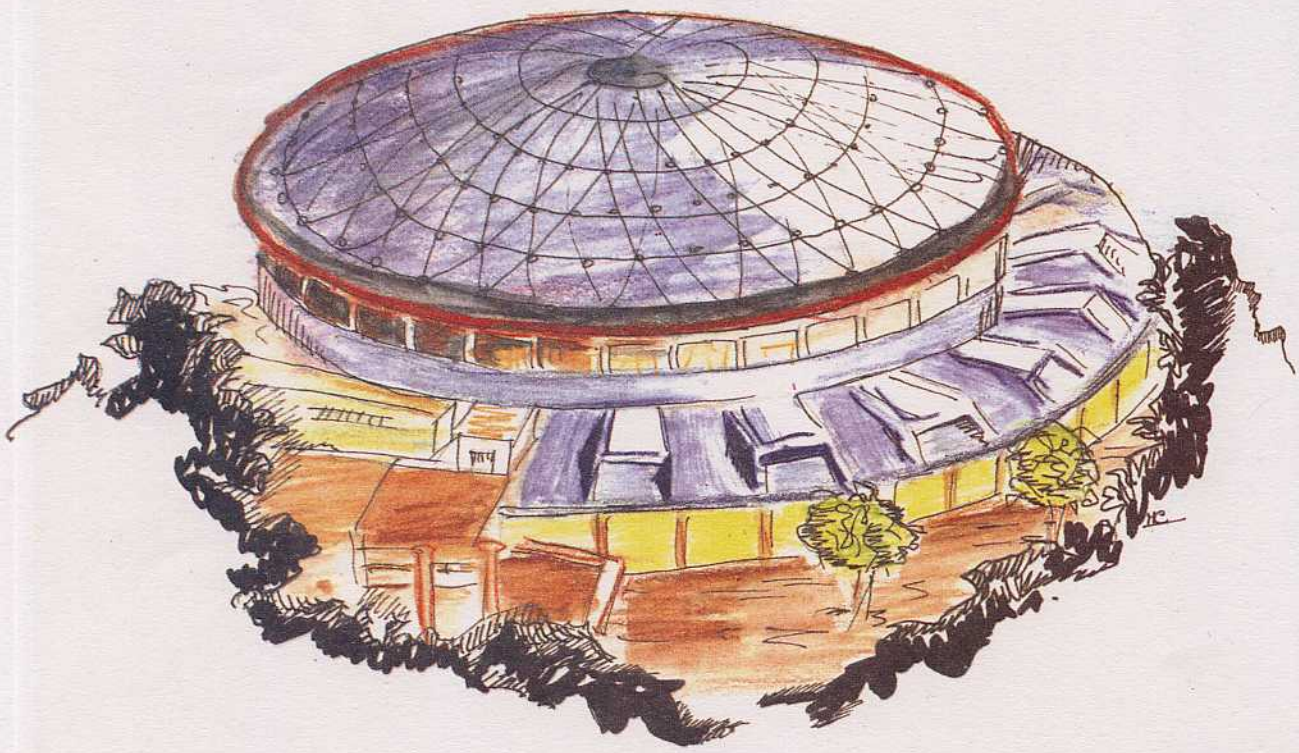
Submitted to Nucl. Instr. & Meth. in Phys. Res. A

LNF-93/006 (P)
8 Febbraio 1993

M. Castellano, L. Catani, M. De Giorgi, M. Ferrario, G. Fuga, S. Kulinski, M. Minestrini, P. Patteri, S. Tazzari, F. Tazzioli:

ON LINE CALORIMETRIC MEASUREMENT OF THE QUALITY FACTOR OF SUPERCONDUCTING ACCELERATOR CAVITIES

PACS.: 29.15.Dt



Servizio Documentazione
dei Laboratori Nazionali di Frascati
P.O. Box, 13 - 00044 Frascati (Italy)

INFN – Laboratori Nazionali di Frascati
Servizio Documentazione

LNF–93/006 (P)
8 Febbraio 1993

ON LINE CALORIMETRIC MEASUREMENT OF THE QUALITY FACTOR OF SUPERCONDUCTING ACCELERATOR CAVITIES

M. Castellano, M. De Giorgi, M. Ferrario, G. Fuga, S. Kulinski, M. Minestrini, P. Patteri, F. Tazzioli
INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I–00044 Frascati (RM) Italy

L. Catani
INFN, Sezione di Tor Vergata, I–00173 Roma, Italy

S.Tazzari
Univ. di Tor Vergata, Dip. di Fisica and INFN, Sezione di Tor Vergata, I–00173 Roma, Italy

ABSTRACT

A comparatively precise method to measure the Q factor of installed superconducting cavities is described. Data taken on the cavities of the 25 MeV SC linac LISA, at Frascati, are presented.

1 – INTRODUCTION

The unloaded quality factor Q_o of a resonant cavity is defined as:

$$Q_o = \frac{\omega_o U}{P_c} \tag{1}$$

where $\omega_o = 2\pi f_o$ is the radian resonant frequency, U the energy stored in the cavity and P_c are the ohmic losses on the cavity walls.

When the cavity is part of an accelerator, the coupling to the RF generator is determined by beam loading and is usually described by an external quality factor, Q_e, that accounts for the power lost through the coupling port; a further power loss occurs through the field probe, and is described by the factor Q_a.

Q_e is normally several orders of magnitude lower than Q_0 so that, unless the coupling can be varied by unpractically large factors, the unloaded value of Q can not be determined in the

usual way, i.e. from the decay time constant, τ, of the stored energy, because the latter, given by

$$\tau = (2Q/\omega_0) \quad \text{with} \quad (1/Q) = (1/Q_0) + (1/Q_e) + (1/Q_a), \tag{2}$$

is dominated by Q_e. Q_0 has therefore to be determined by other methods, typically by calorimetric measurements.

The general scheme consists in measuring the average power loss on the walls calorimetrically, at a known on–axis electric field level, in computing the stored energy from the electric field configuration and the geometry of the cavity by means of well known computational codes such as Superfish, and in finally determining Q_0 from eq. (1). The power loss is evaluated from the evaporation rate of the liquid Helium (LHe) bath in which the cavities are immersed, using the heat of evaporation figure corresponding to the actual pressure and temperature of the bath.

When the cryostat is filled from a dewar and the gas outlet port is accessible, the evaporation rate can be directly measured by bringing the outgoing gas to room temperature and measuring the flow rate with a flow meter.

When instead the cryostat is connected to a refrigerator, as it is the case for accelerators, the measurement of the flow rate is rather more difficult and inaccurate: it is usually done by inserting a throttling diaphragm in the gas return line and measuring the pressure drop across it, from which the flow rate can be calculated. In addition to other causes of inaccuracy, the introduction of a pressure meter does often perturb the operation of the cryogenic system [1].

To measure the unloaded Q factor of the installed LISA cavities we have therefore devised a new, relatively accurate method, based on the measurement of the rate of change of the liquid Helium level in the cryostat. A description of the procedure and of the results obtained is given below.

The completely integrated, automatic data acquisition system provided by the LISA control system has been utilized to monitor all relevant signals from the cryogenic plant, the RF and the cryostat instrumentation. Data were graphically displayed on the control consoles, providing easily readable, on–line monitoring of the overall process and of correlations between parameters, a feature that proved very helpful. Stored data were immediately available for quasi on–line analysis.

2 – DESCRIPTION OF THE LISA CAVITY AND CRYOSTAT

A sketch of the cryostat is shown in Fig. 1: the 4–cell, bulk Nb cavities, are immersed in a LHe bath at an equilibrium temperature of 4.5 K.

The LHe vessel is connected to the refrigerator cold box by two lines: one for liquid and gas inlet, the other for gas return. The inlet flux can be modulated by a valve, that can be operated either automatically or manually.

The LHe vessel is partially filled with Aluminium fillers so that the total net liquid volume is 80 liters; it is insulated from the outside in the standard way, using a radiation shield cooled by an independent 40–80 K gas line, superinsulation layers and isolation vacuum.

It is equipped with a liquid level probe consisting of a NbTi wire of which the portion immersed in LHe becomes superconductive. A current is passed through the wire and the voltage drop across the normal part is measured by two separate sensing wires that carry no current.

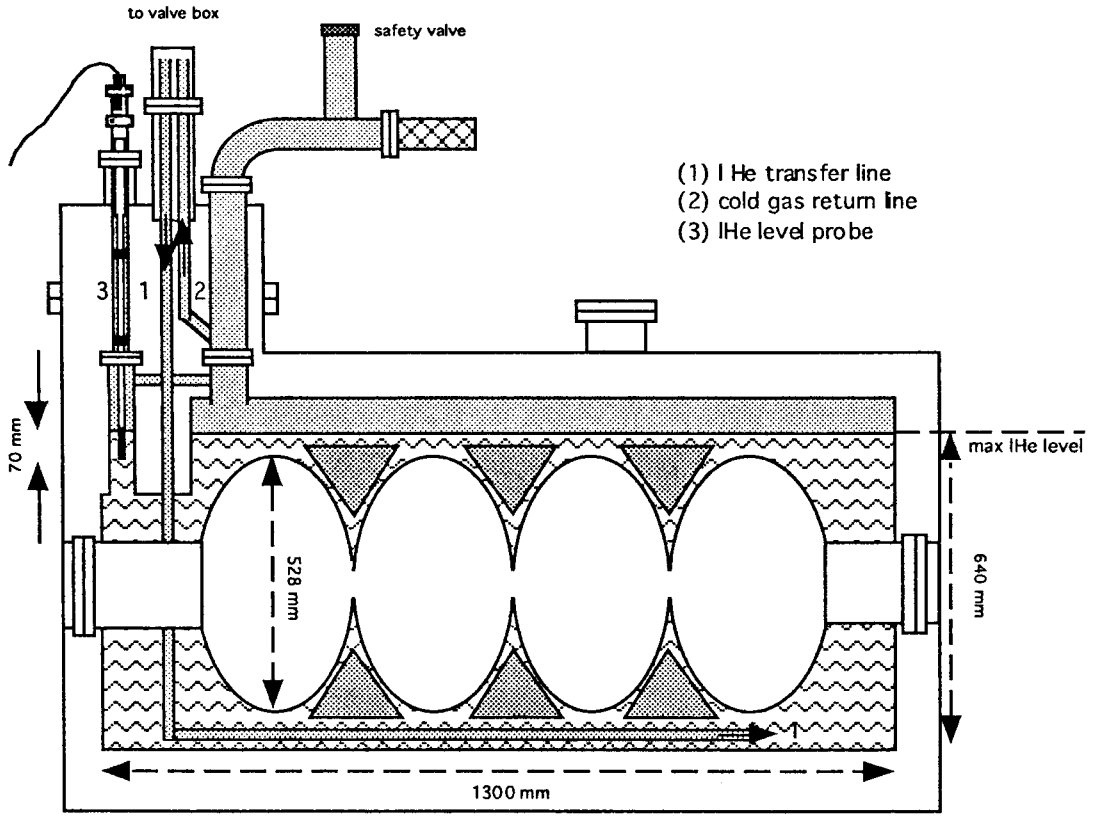


FIG. 1 – Schematic view of the LHe distribution in the LISA cryostats.

The probe penetrates only the upper part of the LHe vessel: the (normalised) inverse of the voltage drop indication ranges from 100%, corresponding to the completely full condition, to 20% when the liquid level is flush wih the uppermost surface of the cavities.

The liquid level signal is fed back to the refrigerator control system that acts on the LHe inlet valve so as to keep the level constant (on average).

In fact, because of the system parameters and the way the control system operates, in the automatic feed–back mode the level undergoes a periodic saw–tooth-like oscillation of about 20% peak–to–peak of its average value, corresponding to 14 mm, with a time constant of several minutes.

In automatic operation the system is therefore never in a true instantaneous equilibrium state; a temporary true equilibrium can only be achieved, for a given heat load, by manually fixing the setting of the LHe inlet valve so that the incoming liquid flux exactly compensates the load.

A heating resistor, mounted on the outside of the LHe vessel, used to speed–up the warm–up process, is also utilised to apply controlled heat loads to the refrigerator.

The bath pressure is monitored using a pressure gauge with analog voltage output.

3 - ELECTRICAL PARAMETERS OF THE ACCELERATING CAVITY

The energy stored in the cavity is related to the cavity shunt impedance, R, through:

$$\frac{R}{Q_o} = \frac{V^2}{\omega_o U} \quad \text{with} \quad R = \frac{V^2}{P_c} \tag{3}$$

where V is the on–axis accelerating potential and the ratio R/Q_0, that depends only on the geometry of the cavity, is directly obtainable from the computer codes mentioned earlier.

Indicating with L the cavity active length, with E_a the average accelerating field and with P_c the power loss on the walls, the following relations can be written:

$$V = LE_a = \left[\left(\frac{R}{Q_o}\right) Q_o P_c\right]^{\frac{1}{2}} = \left[\left(\frac{R}{Q_o}\right) Q_a P_a\right]^{\frac{1}{2}}; \tag{4}$$

the second equation expresses the accelerating potential as a function of the power P_a extracted through the field probe and the probe external Q, Q_a.

Q_a depends only on the geometries of the cavity and of the probe, and can be evaluated by standard electronic techniques with the cavity either at room temperature or cold, Q_0 is obtained from the ratio of equations (4)

$$Q_o = Q_a P_a / P_c \,, \tag{5}$$

so that from the second of the (4), one sees that, to find the field E_a one has only to additionally measure P_a.

The final accuracy on Q_0 is of course linearly dependent on the the error on the measurement of Q_a. We compute Q_a from the formula

$$Q_a = 2Q_e(1 + S_{11}) / S_{21}^2 \tag{6}$$

where S_{i1} are the scattering parameters of the cavity considered as a two–port network, measured using a network analyzer after installation of the cavity on the accelerator. Coefficient S_{11}, representing the reflected fraction of the ingoing signal, is positive and very close to 1 when the cavity is cold; our estimate of the measurement accuracy, including possible systematic effects, is ± 3 %. The loaded quality factor $Q \approx Q_e$ is determined from the width of the resonance curve, that can be measured very accurately (~ $\pm 10^{-3}$). Last, the error on the transmission coefficient S_{21}, is again estimated to be of the order ±3 %. The overall error on Q_a is therefore of the order of ± 10 %. We finally find, for cavity n.1:

$$Q_a = (3.4 \pm 0.4)\ 10^{11} \tag{5c}$$

Other relevant parameters of the same cavity, built (as all LISA others) by Siemens/Interatom, are collected in Table I.

Table I – Parameters of LISA cavity n.1.

L	f_o	R/Q_o	Q_e	Q_a
1.2 m	499.8 MHz	460 Ohm	4.5×10^6	$(3.4 \pm 0.4)\ 10^{11}$

4 – DESCRIPTION OF THE CALORIMETRIC METHOD

The relevant parameter for a calorimetric measurement is the LHe evaporation rate, but we actually measure the level of the liquid in the cryostat as a function of time instead: the level is related to the liquid volume through a simple geometrical relation that has been computed from the known vessel geometry and probe position, and the rate of change of the volume at constant temperature and pressure, dV/dt, is in turn simply proportional to the rate of evaporation.

Note that when the pressure (and therefore the temperature) is not constant, a correction has to be introduced because pressure variations induce temperature variations that in turn cause the density of the liquid to change, affecting, for a given liquid mass, the liquid volume and therefore the liquid level. By expanding the density to first order in the pressure changes, ΔP, around the average pressure value, one can easily show that the deviation of the evaporated volume from the linear time dependence expected for a fixed load, ΔV, should be a linear function of ΔP :

$$\Delta V = V_0 + a\,\Delta P. \qquad (7)$$

Coming to the details of the measuring technique, we first tried to measure the cryostat static losses by closing the LHe input valve and recording the behaviour of the liquid level level as a function of time.

Because the liquid and the gas are no longer in equilibrium, the pressure is found to execute slow, rather large excursions, as shown e.g. in Fig. 2 where a typical measurement run is displayed.

The liquid level rate of change has therefore to be reduced to constant pressure before deriving the actual evaporation rate.

That eq. (7) is actually verified over the range of parameters spanned by the measurement is shown by the data of Fig. 3. Error bars are only statistical, determined by repeated measurements during a steady equilibrium state.

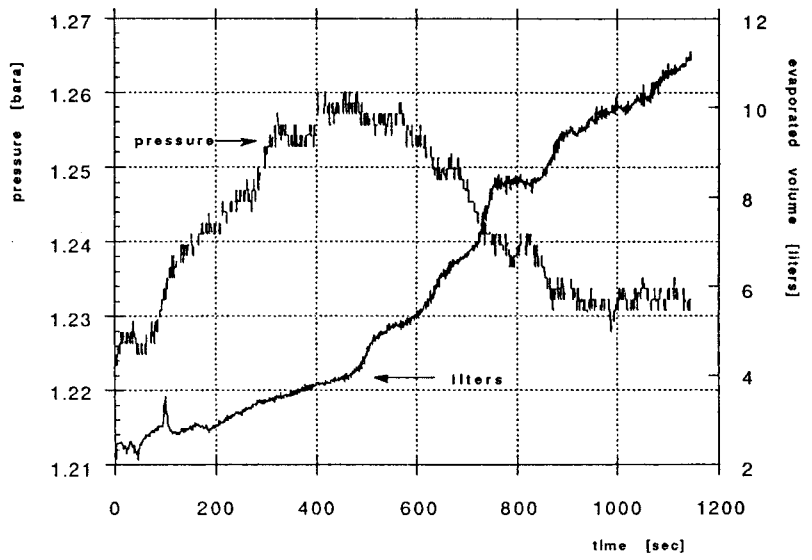


FIG. 2 – LHe inlet valve closed: behaviour of pressure and liquid level vs. time.

A linear fit to the data of Figure 3 gives the following formula to reduce all data to a standard pressure value of 1.2 ABar:

$$\Delta V = 67(\pm 1.6) - 56(\pm 1.3)\ P \qquad (8)$$

with ΔV expressed in in liters and P expressed in ABar. The χ^2 value of the fit is 2.2, indicating that systematic effects due to the dynamic behavior of the complex thermodynamic system are present; the linear correlation factor, R, is nevertheless very good (.97 for 100 data points). In any case, the corrections introduced by eq.(8) are small enough, over the entire range covered by the data, that the effect of systematic deviations from the linear behavior of eq.(8) is negligible.

The measured coefficients are well consistent with what expected from computing the density change from the temperature variation due to the change in gas pressure, using LHe data found in the literature. Furthermore, when applied to data taken at different, constant input powers into the bath, eq. (8) always leads to a reduced evaporation rate that is, as it should, constant to within the errors.

Reduction according to eq.(8) has consequently been performed on all data.

The evaporation rate after reduction is shown in Fig. 4 for the case (static losses) described by the data of Fig. 2; the linear fit gives: dV/dt = .480±.001 liters/min at the equivalent constant pressure of 1.20 ABar with a reduced χ^2 of about 1 and R=.997. Note the small value of the statistical error, due to the large number of data points and their smooth behavior.

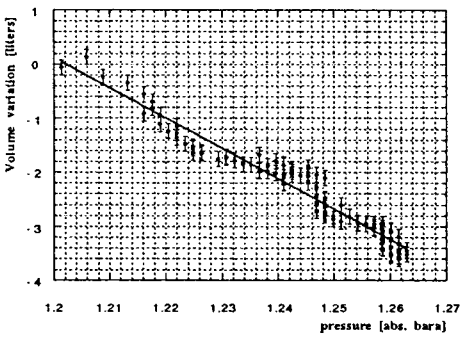


FIG. 3 – Deviation of the evaporation rate from a constant vs. pressure; closed LHe inlet valve.

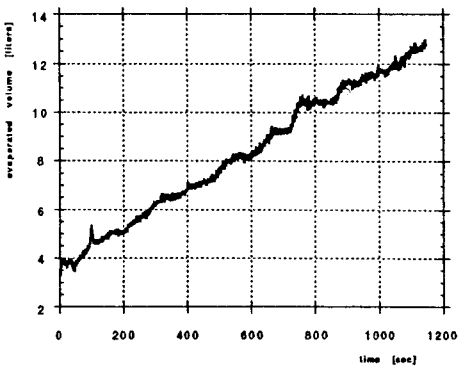


FIG. 4 – Level rate of change: data of Fig. 1 after reduction.

The cavity quality factor can be evaluated by simply turning on the RF once the input LHe flow is in fixed equilibrium with the static losses and measuring the resulting level rate of descent. We, however, observe that pressure variations induced by the switching–on of additional amounts of RF power large compared to the static losses, are large and often exceed the limits within which the linear correction described above can be applied.

We therefore find it helpful to start from a heat input level that is comparable to or larger than that introduced by the RF. This also helps achieving a steadier equilibrium because the refrigerator, designed to handle the maximum load, does not perform at its best when only lightly loaded.

In practice, using the heating resistors, we first introduce a well known amount of power, much larger than that corresponding to static losses, into the cryostat, switch the refrigerator to automatic and wait until an (average, imperfect) equilibrium state is reached. Under such conditions the LHe inlet valve setting performs small oscillations around its average position: once the latter position has been determined, the valve is blocked there manually.

The fixed LHe input then almost exactly compensates the overall heat input and the level remains sufficiently constant for a rather long time (order of tens of minutes).

We can then switch on the RF and measure the liquid level fall rate, only due to P_c. The gas–liquid equilibrium is much less perturbed, and pressure variations are strongly reduced. Additional corrections for slight deviations from a perfect equilibrium during RF–off time, that would otherwise become the largest sources of error in the procedure, can be easily applied.

Also note that measurements can be performed at different RF peak power levels under almost identical experimental conditions, by pulsing the radiofrequency and varying the duty cycle in such a way as to keep the average RF power constant .

Fig. 5 shows a sample of data taken with this technique on the cavity n. 1.

The RF power corresponds to an accelerating field of 2.8 MV/m; it was switched–on after an equilibrium state had been reached with 30 W of heat added to the static losses. The RF duty cycle was 25% (one 200 ms pulse every 800 ms).

The corresponding evaporation rate was 1.91 liters/min.

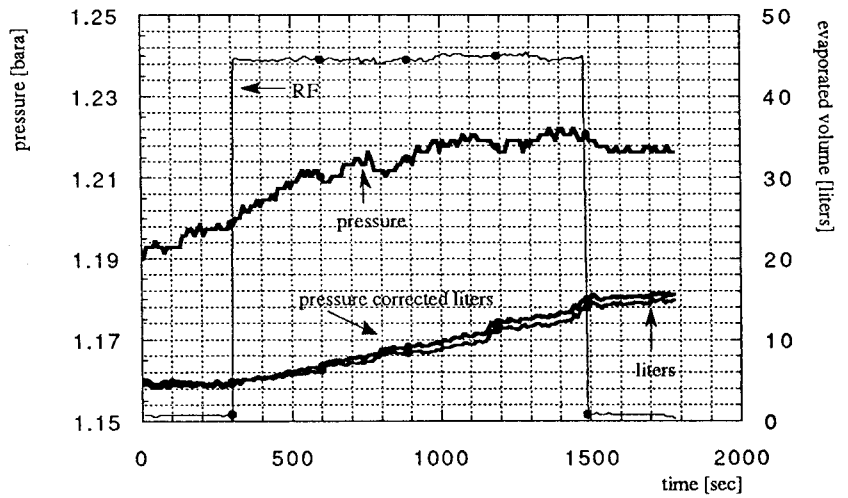


FIG. 5 – RF power on: behaviour of the pressure and liquid level vs. time.

The thermal power input causing the measured fall rate can in principle be computed using the evaporation heat literature figure corresponding to the given experimental conditions: at our nominal operating temperature of 4.6 K, the theoretical conversion coefficient, r, is 0.030 l/min of LHe per watt of input power [2]. Using the theoretical value of r would however be rather inaccurate because of the uncertainty on the actual bath temperature: we therefore measured r directly utilising the heating resistors.

Starting from an equilibrium state obtained providing 20 W of input power from the resistors, we measured the liquid volume variation as a function of heat power input: very careful measurements were performed at two power levels symmetrically positioned around the equilibrium value and a third point was measured, less accurately, to check on linearity.

The resulting measured coefficient is r = 0.037±.0015 liters/min/W, in rather good agreement with the computed result, considering the uncertainty of the latter.

Using the experimental conversion coefficient, the overall static losses of the cryostat are found to be 13 W, considerably larger than the 6 W measured at the factory.

The discrepancy was expected and is fully consistent with the fact that during factory measurements the radiation shield was cooled by the gas evaporated from the bath and was therefore at a temperature considerably lower than under normal operating conditions,when the shield is connected to a at 40–80 °K cooling line, and with the effect of additional penetrations (such as level probe,.etc) present in the cryostat fully operational configuration and not in the factory–test one.

5 – RF MEASUREMENTS

The power coupled–out through the field probe was measured in the control room, on a 50 ohm load, with a RF voltmeter. The measured attenuation of the transmission line connecting the probe to the voltmeter was –12.5 dB.

With the values of Tab. I, using eq.5 and calling V_m the power meter voltage reading one then obtains :

$$E_a = h\, V_m \quad \text{with} \quad h = 6.21 \text{ MV/V/m} \tag{9}$$

Furthermore, using eq.6, one finds in MKS units :

$$Q_o = \frac{Q_a P_a}{P_c} = \frac{3.4\times10^{11} V_m 10^{1.25}}{50 P_c} = \frac{1.209 V_m^2 10^{11}}{P_c} \quad , \text{ with } P_c = (dV/dt)/r. \tag{10}$$

6 – CONCLUSIONS

In Table II we show the results of several measurements at various field levels and at different stages of RF conditioning.

Table II – Q measurement data.

V_m (V)	0.224	0.263	0.359	0.443	0.446	0.496	0.508	0.565
duty cycle	cont.	cont.	cont.	25 %	25 %	20 %	20 %	20 %
Ω (l/s)	0.194	0.214	0.292	1.01	1.41	1.92	2.75	9.55
P_c (W)	5.24	5.78	7.89	27.2	38.16	51.89	74.32	258.1
E_a(MV/m)	1.39	1.63	2.223	2.75	2.77	3.08	3.15	3.51
$Q / 10^9$	1.2	1.4	2.0	0.9	0.6	0.6	0.4	0.15

Note that, at the time of these measurements, the cavity was not fully conditioned; a maximum accelerating field of 3.85 MV/m had been reached (limited by e–loading) but no Q measurement was taken there.

The highest low–field Q value listed in the table ($2 \pm .3 \times 10^9$) is in agreement with the zero field value measured calorimetrically at the factory ($2.\times 10^9$), where the gas return line was accessible and the gas flow could therefore be directly measured, at room temperature, with a flow meter.

ACKNOWLEDGEMENTS

The authors express particular thanks to M. Niggli of LINDE Company for many helpfull discussions for optimizing the performances of the refrigerator system and to R. Ceccarelli and R. Lanzi of the LNF cryogenic group for assistance during operations.

REFERENCES

[1] – *R. Byrns et al.*: Cryogenic Distribution System (CDS) for Eight HERA Superconducting RF Cavity Cryostats – Proc. 5th Workshop on RF Superconductivity, DESY Report M–92–01 (1992)

[2] – *V.J. Johnson ed.*: A Compendium of the Properties of Materials at low Temperature (Phase I) – WADD Technical Report 60–56 (1960)