(NbTi)N and NbTi Coatings for Superconducting Accelerating Cavities

Benvenuti C., Calatroni S., Hauer M., Minestrini M.*, Orlandi G.**,
Weingarten W.
CERN, CH-1211 Geneva 23

* Present Address: INFN Laboratori Nazionali di Frascati, P.O. box 13, I-00044 Frascati RM
** ASP Fellow at CERN (ASP = Associazione Sviluppo Scientifico Piemonte, Turin, Italy)

Abstract

In the framework of a study of new superconducting coatings, aiming at improving LEP cavities performance at 4.2 K, single-cell 500 MHz copper cavities have been coated with thin films of (NbTi)N. Coatings have been carried out by reactive sputtering starting from NbTi cathodes of two different compositions, $Nb_{0.55}Ti_{0.45}$ and $Nb_{0.40}Ti_{0.60}$ (atomic percentages).
The highest T_c on samples so far obtained is 15.8 K, while the transition temperature of the best cavity is about 14.5 K. The BCS surface resistance of this cavity measured at 4.2 K is 9 nΩ, more than four times lower than the corresponding value of niobium coated copper cavities (Nb/Cu). However, the residual surface resistance is 18 nΩ, higher than for Nb/Cu (about 5 nΩ). These combine to provide a Q_0 value at low fields and at 4.2 K about two times higher than for Nb/Cu. However, a strong Q_0 decrease has been observed when increasing the accelerating electric field, resulting in Q_0 lower than for Nb/Cu above about 2.5 MV/m.

1. Introduction

In order to decrease the surface resistance at 4.2 K of coated superconducting cavities, the use of materials with $T_c > 9.2$ K is mandatory.
Critical temperatures above 17 K are reported in the literature [1, 2] for NbN and (NbTi)N films deposited by reactive magnetron sputtering. This technique consists in adding nitrogen to the argon used to produce the sputtering discharge, making use of Nb or NbTi cathodes.
The advantages of this choice are first that Nb and NbTi cathodes can be produced easily and, on the other hand, that Nb based nitrides are less sensitive to crystalline disorder (hence to radiation damage) than other materials of similar T_c (for instance, the A15 compounds). A further advantage is that the coating technology is mastered since sputtering configurations for cavity coating have been extensively studied and used at CERN during the last 10 years [3, 4].

Among all the possible NbTi alloy compositions, $Nb_{0.40}Ti_{0.60}$ and $Nb_{0.55}Ti_{0.45}$ have been used. The $Nb_{0.40}Ti_{0.60}$ has been selected because more easily available (this alloy is used for producing superconducting cables) while the $Nb_{0.55}Ti_{0.45}$ should represent the best compromise between critical temperature and normal state resistivity [2]. In the latter case, a Q_0 improvement of about a factor 30 with respect to Nb may be hoped for.

2. *Experimental Procedure and Results on Samples*

(NbTi)N coatings have been produced by magnetron sputtering both on 500 MHz copper cavities and on small samples (quartz and copper) placed inside a stainless steel cavity equipped at its equator with a rotatable sample holder. Keeping the cathode voltage, discharge current and Ar base pressure constant, several samples have been coated during the same run at different values of the N_2 initial pressure.
Quality of samples has been monitored by measuring T_c and, at transition and ambient temperature, d.c. resistivity. Best values on samples have been obtained at a discharge voltage of 450 Volts, discharge power of 7 kW, Ar pressure 1.5×10^{-3} mb and initial N_2 pressure ranging from 3.5×10^{-2} mb to 3.7×10^{-2} mb depending on cathode composition.
The optimum value of N_2 pressure, corresponding to films of the required stoichiometry, is found for the maximum N_2 consumption [5, 6] (see fig. 1). Lower or higher N_2 pressures lead respectively to under or oversaturated films of poorer quality (see fig. 2). The best results obtained so far on samples are summarised in Table 1.
The copper cavities, prepared according to the standard CERN procedure for Nb coatings [4], have been coated with (NbTi)N only in the resonating cell; cut-off tubes have been coated with a Nb film.

Less attention has been paid to NbN because of its lower T_c and the more problematic N_2 pressure stabilisation initially experienced with this material.

	T_c [K]	ρ [$\mu\Omega$cm]	RRR	Q_0 [1×10^9]	λ [Å]
$Nb_{0.40}Ti_{0.60}$	9.0	80	1.14	1.3	3000
$Nb_{0.55}Ti_{0.45}$	9.6	50	1.27	2.6	2300
$(Nb_{0.40}Ti_{0.60})N$	14.7	50	1.25	37	1800
$(Nb_{0.55}Ti_{0.45})N$	15.8	70	1.13	55	2100

Table 1. Measured best values for T_c, room temperature resistivity ρ, RRR, for NbTi and (NbTi)N samples of different composition. Under Q_0 and λ are indicated the calculated values for the BCS part of Q_0 and for the penetration length. Calculations have been carried out numerically following [7] in the normal skin effect approximation and with a strong coupling factor of 4.

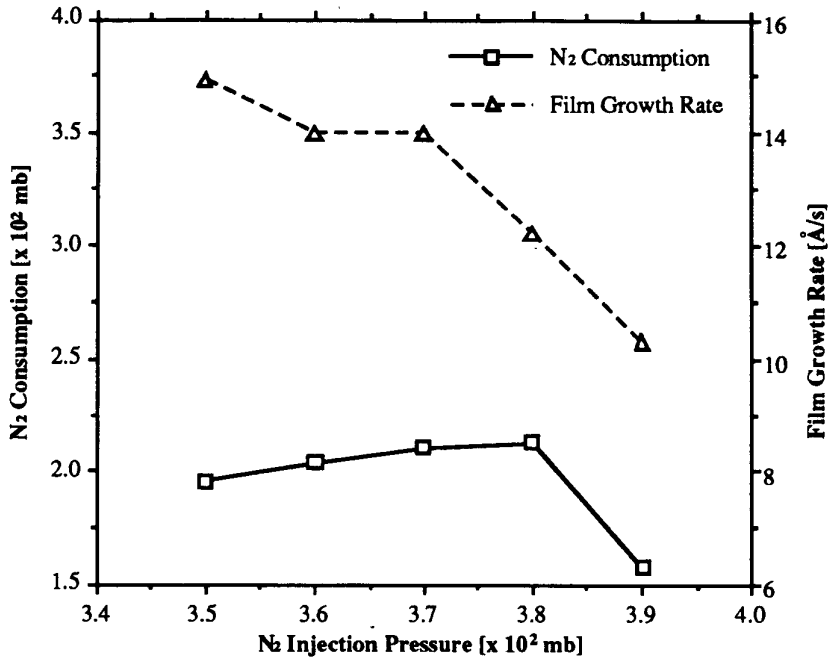

Figure 1. Nitrogen consumption during the coating as a function of the N_2 injection pressure (measured in the absence of discharge). The N_2 consumption is defined as the difference between the N_2 injection pressure and the equilibrium N_2 pressure during the coating. Also shown in the figure is the film growth rate dependance on the N_2 injection pressure.

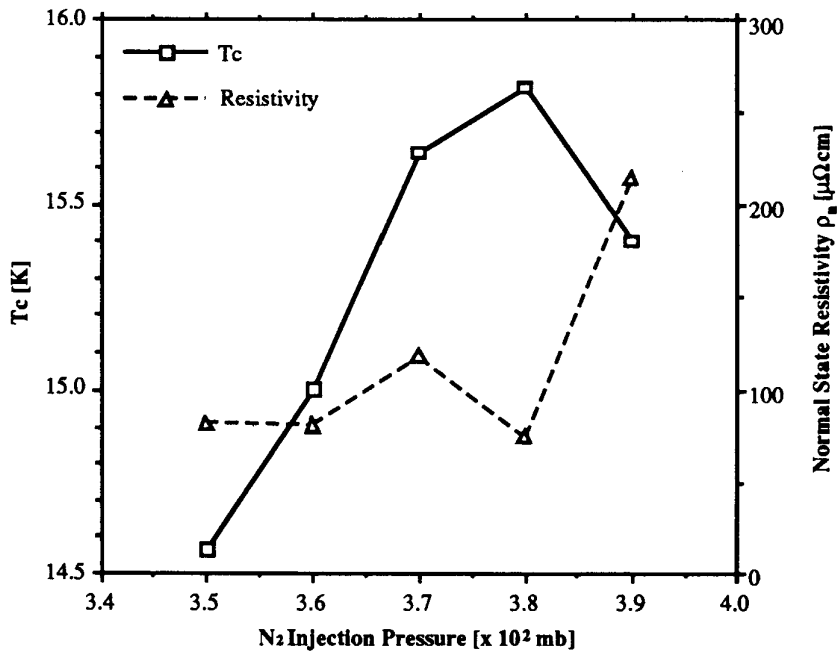

Figure 2. Variation of T_c and ρ_n (at room temperature) as a function of the N_2 injection pressure. Discharge parameters: V_{cath} 450 V, power 7 kW, Ar pressure 1.5×10^{-3} mb.

3. Coatings of Cavities: Results and Discussion.

The results obtained with the first cavity coated with a 2.5 µm thick film of $(Nb_{0.40}Ti_{0.60})N$ are shown in fig. 3 (cavity 6).
The surface resistance at low field and 4.2 K is 70 nΩ, of which 20 nΩ represent the BCS contribution (corresponding to a T_c of about 12.5 K) and 50 nΩ represent the residual resistance. The BCS resistance is about half that of Nb coatings, while the residual resistance is about 10 times higher.
Electron loading started at 3 MV/m; 5 MV/m have been reached after 8 h of helium processing.

The results obtained on cavity 6 could not be reproduced on other cavities coated with the same parameters. A typical result is shown in fig. 4 (cavity 8). In this case, both the initial Q_0 values at 4.2 K and at 2.7 K are lower than for cavity 6 and the $Q_0(E)$ curve slope is much higher, resulting in very poor RF performance.
Whenever poor results of this type have been obtained, a sudden N_2 pressure increase had been noticed during coating. However, coating had been continued to obtain the required film thickness.

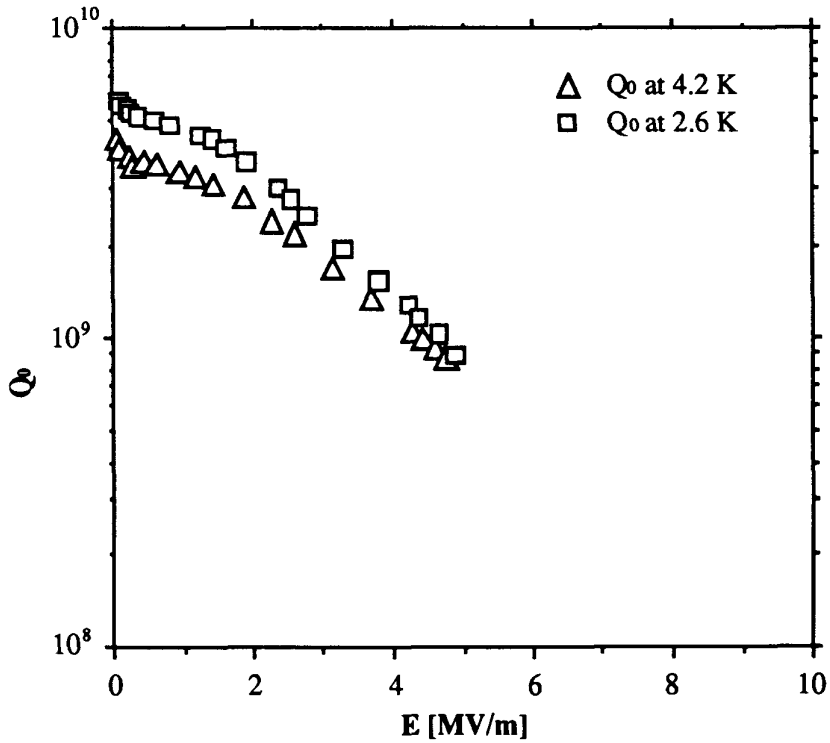

Figure 3. $Q_0(E)$ for 500 MHz single cell cavity 6 coated with a 2.5 µm thick film of $(Nb_{0.40}Ti_{0.60})N$. The coating parameters are those indicated in fig.2.

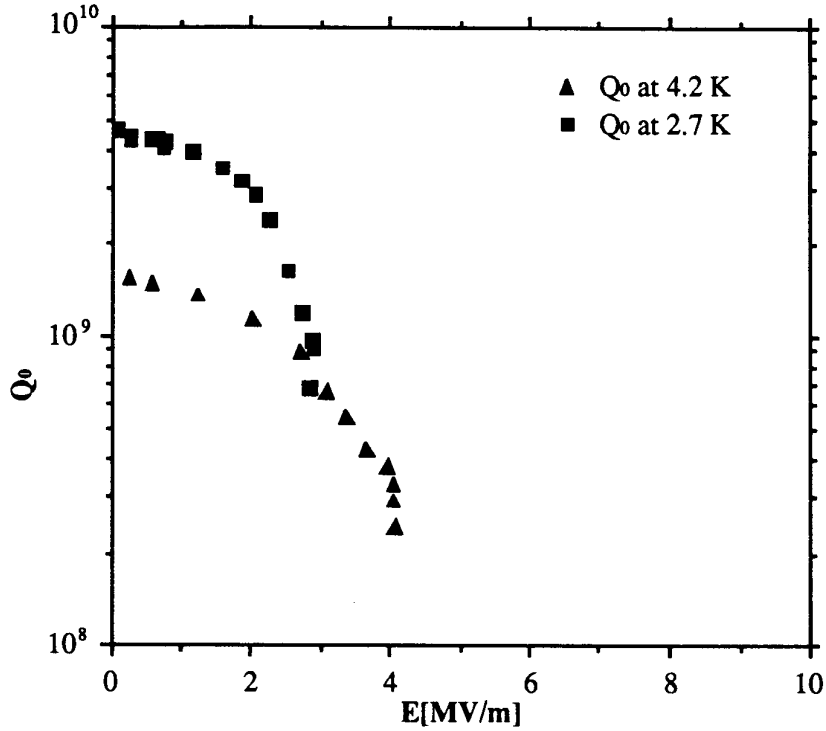

Figure 4. $Q_0(E)$ for 500 MHz single cell cavity 8 coated with a 1.1 μm thick film of $(Nb_{0.40}Ti_{0.60})N$. Same coating conditions as for cavity 6 of fig. 3.

As already pointed out (§ 2) the N_2 pressure increase is detrimental because it results in oversaturated films of poor performance.
It has been found that the cathode keeps memory of previous coatings, in spite of been sputter cleaned between coatings inside the stainless steel cavity. This results in a slight difference in the N_2 pressure at the beginning of the discharge, which may develop catastrophically during the coating and lead to the unwanted pressure rise.
This situation has been investigated by reproducing the same N_2 pressure increase during sample coating. The results show that T_c in this case is about 10 K, which corresponds to that calculated from RF measurements of cavity 8. To avoid this risk, coating has been carried out starting with a N_2 injection pressure slightly below the optimum value. Meanwhile, the cathode made of $Nb_{0.40}Ti_{0.60}$ had been replaced by a $Nb_{0.55}Ti_{0.45}$ cathode, which gave better results on samples (see table 1).
In spite of the reduced initial N_2 pressure, its sudden increase has been noticed towards the end of the coating process. At distinction with the previous cases, the coating has been stopped, corresponding to a film thickness of 1.7 μm. The result obtained (cavity 10) is shown in fig. 5.

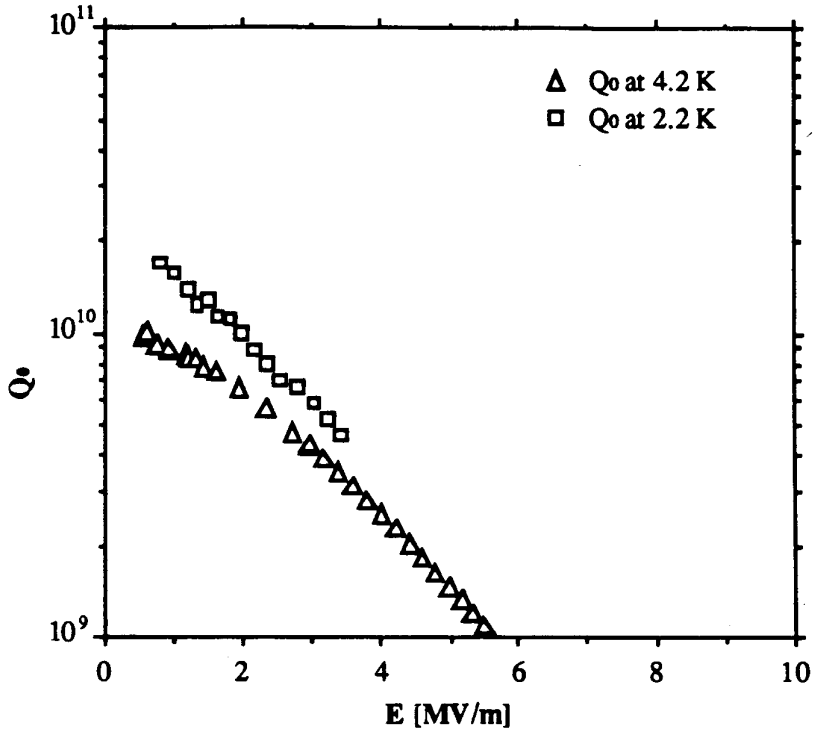

Figure 5. $Q_0(E)$ for 500 MHz single cell cavity 10 coated with a 1.7 μm thick film of $(Nb_{0.55}Ti_{0.45})N$.

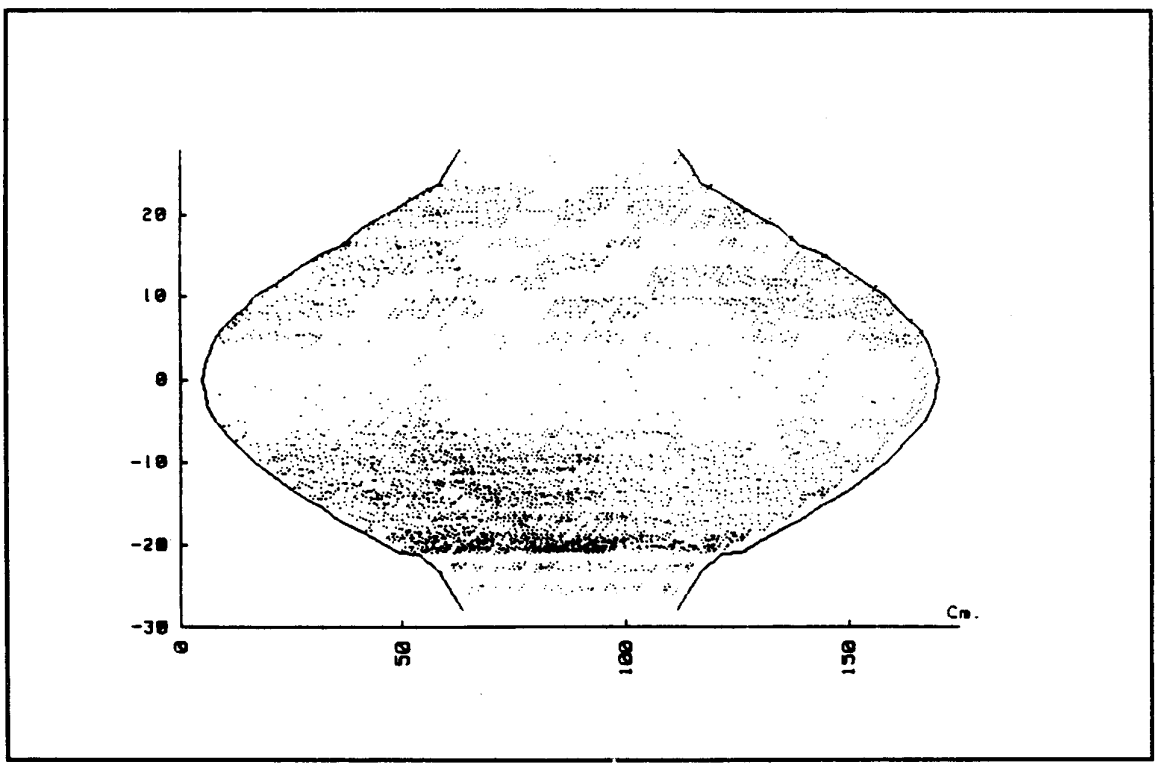

Figure 6. Temperature map measured on cavity 10 at 5.7 MV/m. There is no evidence for the presence of a "hot spot", indicating a localised accidental defect in the coating.

At low field and 4.2 K the surface resistance of this cavity may be decomposed in a BCS contribution of 9 nΩ (more than 4 times lower than for Nb/Cu, corresponding to a T_c of about 14.5 K) and a residual resistance of 18 nΩ.
The Q_0 of this cavity is about a factor 2 better than for Nb coatings at low field, but the fast Q_0 degradation results in lower values above 2.5 MV/m.
As shown by temperature mapping, this degradation is not due to localized accidental defects (see fig. 6).
No electron emission has been noticed up to the maximum accelerating field of 7.6 MV/m (limited by the available RF power).

In order to better understand the origin of the observed $Q_0(E)$ degradation, a few cavities have been coated with NbTi films. A similar Q_0 degradation has been noted (see fig. 7), showing that the cause of this phenomenon can not be attributed to the presence of N_2.
No electron emission has been noticed, for the cavity shown in fig. 7, up to the maximum accelerating field of 9 MV/m.

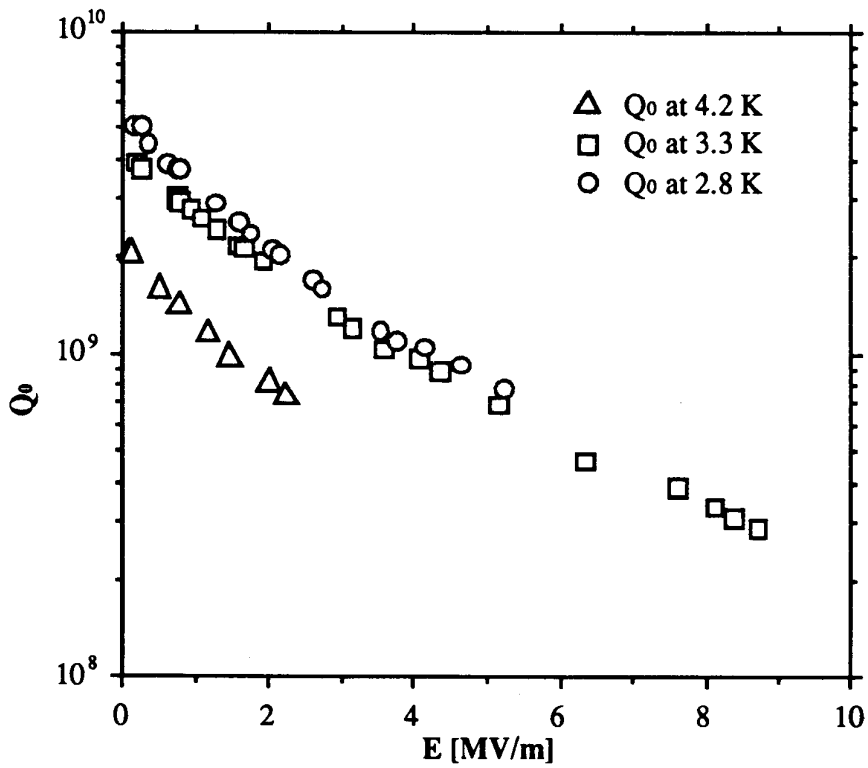

Figure 7. $Q_0(E)$ for 500 MHz single cell cavity 9 coated with a 3.6 µm thick $Nb_{0.55}Ti_{0.45}$ film. Same coating parameters as indicated in fig. 2.

4. *Conclusions*

Altough the quality of (NbTi)N sputter coated cavities is still inferior to that obtainable by other techniques, as for instance thermal diffusion of Sn to form Nb_3Sn on the surface of a Nb cavity [8, 9], the reported results are encouraging in many respects. In spite of the Q_0 degradation with increasing accelerating field, the performance of the $(Nb_{0.55}Ti_{0.45})N$ coated cavity almost fulfils the specifications for the bulk Nb cavities ordered to industry for LEP 200 (see fig. 8).
Furthermore, the very low thermal losses at the equator of cavity 10 (see fig. 6) show that better cavity performance could be obtained provided that a more uniform quality of the coating be achieved.
The same conclusion may be derived from fig. 9, which shows that cavity coating T_c's are still below those of best samples. If the best quality could be reached, a Q_0(BCS) improvement of a factor 10 with respect to Nb/Cu could be achieved.
The major obstacles towards improving the performance of (NbTi)N coated cavities are represented by the large residual resistance and the important Q_0 degradation with increasing the accelerating field. These points will be the object of further studies.
Some evidence seems to emerge that electron field emission from the coatings is somewhat lower than for Nb based cavities, but this may as well be a consequence of our improved rinsing procedure and more experiments are required to prove or disprove this observation.

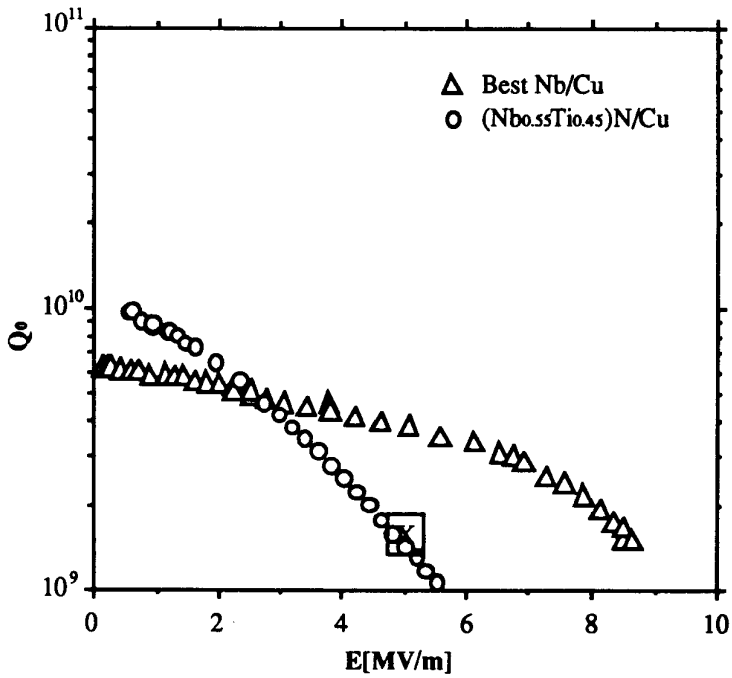

Figure 8. Q_0(E) at 4.2 K for the best Nb (number 4) and (NbTi)N (number 10) coated cavities. The X represents the specified value for LEP Nb bulk cavities scaled according to the square of frequencies.

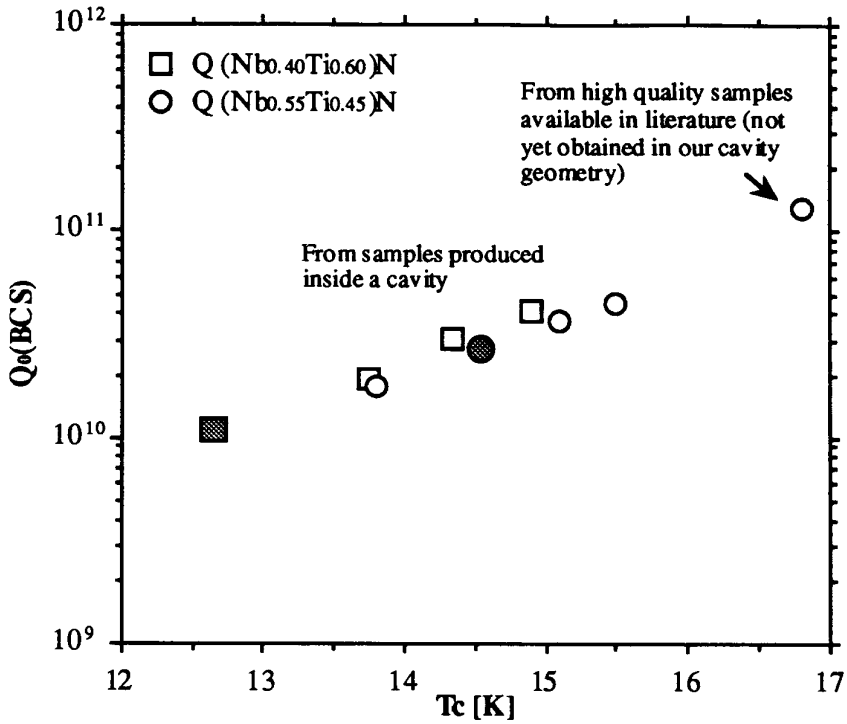

Figure 9. Calculated (□, ○) and measured (■, ●) BCS Q_0 values for 500MHz (NbTi)N coated cavities at 4.2 K. For comparison, this value for the best Nb/Cu case is 6.8×10^9.

References

[1] J. C. Villegier, L. Vieux-Rochaz, M. Goniche, P. Renard, M. Vabre, IEEE Trans. Mag. MAG-21, 2, 498 (1985).
[2] R. Di Leo, A. Nigro, G. Nobile, R. Vaglio, J. Low Temp. Phys. 78, 1/2, 41 (1990).
[3] C. Benvenuti, N. Circelli, M. Hauer, Appl. Phys. Lett. 45, 5, 583 (1984).
[4] C. Benvenuti, D. Bloess, E. Chiaveri, N. Hilleret, M. Minestrini, W. Weingarten, Proc. of the III Workshop on RF Superconductivity, ANL-PHY-88, Argonne (1988), p. 445.
[5] H.-O. Blom, S. Berg, T. Larsson, Thin Solid Films 130, 307 (1985).
[6] S. Thakoor, J. L. Lamb, A. P. Thakoor, S. K. Khanna, J. Appl. Phys. 58, 4643 (1985).
[7] S. B. Nam, Phys. Rev. 156, 2, 487 (1967).
[8] G. Arnolds-Mayer, E. Chiaveri, Proc. of the III Workshop on RF Superconductivity, ANL-PHY-88, Argonne (1988), p. 491.
[9] M. Peiniger, M. Hein, N. Klein, G. Müller, H. Piel, P. Thüns, Proc. of the III Workshop on RF Superconductivity, ANL-PHY-88, Argonne (1988), p. 503.