International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity
Legnaro (Italy) – October 9th to12th 2006

REVIEW ON Q-DROP MECHANISMS

Bernard VISENTIN [#]
CEA-Saclay, DSM / DAPNIA / SACM - 91191 Gif / Yvette Cedex – France

Abstract

Manufacturing of radiofrequency cavities by deposition of superconducting thin films has never emerged as an alternative method to the niobium bulk technology because of the poor performances of accelerating fields (E_{acc}) achieved. Nevertheless this established fact could be soon in balance again because of the necessity to use any superconductor else than Nb to overcome actual fundamental limitations.

Historically *R & D* studies have been much more intensive on bulk Nb cavities and performances increased steadily by decisive findings in appropriate chemical, thermal and surface treatments. The purpose of this paper is to give a review of these experimental advances and theoretical explanations to attempt to understand limited performances of thin film cavities and cast a new light on this issue.

INTRODUCTION

Superconducting cavities manufactured by thin film coating of Nb or Nb compounds (Nb_3Sn, NbN, NbTiN…) could be an attractive alternative to bulk niobium cavities in terms of lower cost and higher limits for both critical temperature and superheating magnetic field. But the damning disadvantage of thin film cavities is the continuous decrease of the quality factor Q_0 versus accelerating field E_{acc} [1-4] (Fig.1). Due to this Q-drop, the highest value experimentally achieved for the accelerating field is 25 MV/m.

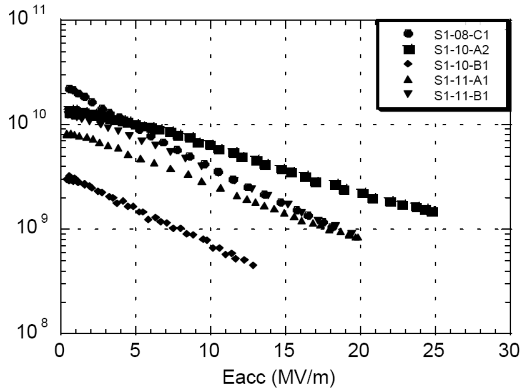

Figure 1: Example of typical Q_0 (E_{acc}) curves at 1.7 K for Nb coatings on copper cavities (1.5 GHz) [3].

In spite of limited performances, Nb coatings are particularly well adapted to large size copper cavities (f < 700 MHz) with thick wall (> 6 mm) whose accelerating field's specification is lower than 15 MV/m.

Nb atoms coating on Cu cavity-substrate can be efficiently achieved by cathode sputtering in a DC magnetron discharge. This technique was first developed at CERN and it is now world-wide applied to build superconducting structures for accelerators such as LHC (400MHz) [5], synchrotron light sources (ELETTRA and SLS at 1.5 GHz, SOLEIL at 352 MHz) [6,7], neutrino factory and muon collider projects at 200 MHz [8].

Nevertheless, other techniques are under studies to improve the thin film structure: Nb ions sputtered by pulsed arc discharge [9, 10] or Nb atoms vaporized by electron gun and then ionized in an ECR (Electron Cyclotron Resonance) plasma [11].

THIN FILM CAVITY Q-DROP

Superconducting energy gap dependence with the magnetic field $\Delta(H)$ could explain the thin film Q-drop, through the low value of the ℓ/ξ_0 key parameter (ratio between the electron mean free path and the coherent length of Cooper pair) [13]. According to the Granular Superconductor Theory, losses should be linked with the nature of the Nb coating itself, due to the penetration of Josephson fluxons in weak links: oxidized sputtered islands in this case. The increase of the thermal resistance at the superconductor-substrate interface could also be put forward as an explanation [12].

On the contrary, other authors associate the limited performances of thin film cavities with less fundamental facts: lower surface resistances could be reached through significant progress in manufacturing process and in preparation cleanness of the copper cavity-substrate [4].

One thing is for sure: more *R & D* on thin film cavities is needed to compare theories with experiments.

BULK CAVITY Q-DROP

Q-slopes also exist in the bulk case, but their origins are probably different. In Fig.2, Q_0 (E_{acc}) curve of the Nb bulk cavity (green data) can be compared to blue data of the thin film cavity. We can notice a softer Q-slope for the bulk cavity at medium accelerating fields and a steeper one above 25 MV/m. Performances of E_{acc} are in both cases limited by the RF power supply available.

However, for the niobium bulk cavity, the high field Q-slope can be removed by baking (Fig.3) at 120 °C for

---

[#] bernard.visentin@cea.fr

2 days [14] and its performances are limited by quench (superconducting breakdown). The quench value can reach a maximum of 42 MV/m for a cavity with a TESLA-type elliptical shape and treated by electropolishing (EP) as shown in Fig.4.

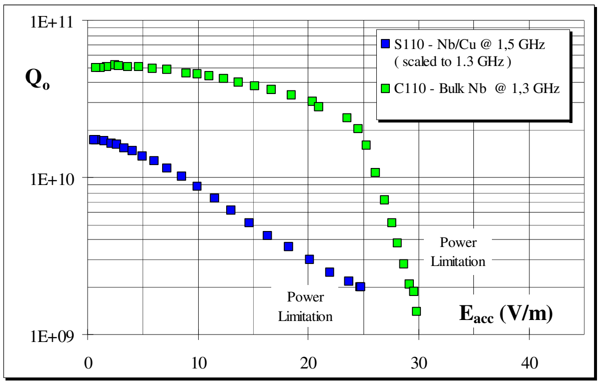

Figure 2: Comparison of Q-drops between thin film (blue) and bulk cavities (green).

Q-DROP MECHANISMS IN BULK CASE

The physical reason of the high field Q-slope removal by baking is a challenging issue and many experiments have been carried out in that way to find an explanation. In parallel, a lot of theories have been pushed forward to explain Q-slope existence.

To assess Q-slope understanding it is necessary to review the latest results with the secret hope to clear up by the way the thin film issue.

In fact, for a bulk cavity, we have to consider three different Q-slopes in the Q_0 (E_{acc}) curve: at low (LF), medium (MF) and high fields (HF) as shown in Fig.3.

Low Field Q-Drop

According to Halbritter [15], the Q-slope at low field is due to the presence of NbO_x clusters in niobium, located at the oxide-metal interface, providing localized states inside the Nb energy gap, therefore increasing the surface resistance.

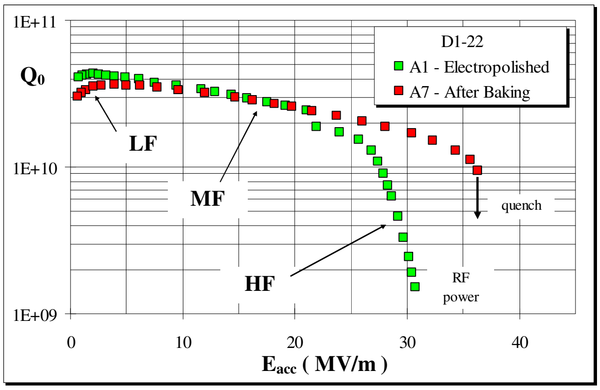

Figure 3: Low Field and High Field Q-slopes modifications after baking.

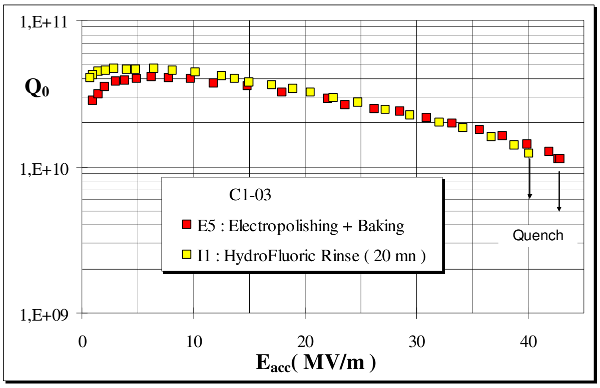

Figure 4: Low Field Q-slope modifications after hydrofluoric acid rinse.

This theory could explain some experimental observations [16]:

- After cavity baking, the LF Q-slope enhancement (Fig.3) could be caused by additional clusters due to the interstitial oxygen diffusion.
- After hydrofluoric rinse of the baked cavity, LF Q-slope is restored as before baking (Fig.4). Considering that hydrofluoric acid just removes the niobium oxide and that a new oxide layer is later rebuilt at the surface, the LF Q-slope origin is necessarily located in the oxide layer or at the oxide-metal interface as NbO_x clusters.

Medium Field Q-Drop

With regard to the Q_0 (E_{acc}) evolution in the medium field range, a linear and quadratic increases of the surface resistance R_S ($\propto 1/Q_0$) on the peak surface magnetic field B_P ($\propto E_{acc}$) have theoretically been established [12, 15].

The linear dependence (Eq. 1) is linked to hysteresis losses due to Josephson fluxons in weak links (oxidation of grain boundaries). As regards quadratic dependence (see Eq. 2), it is caused by a surface heating due to the thermal impedances of Nb and Nb-He interface.

$$R_S = a + bB_P \tag{1}$$

$$R_S = R_0 (1 + \gamma \frac{B_P^2}{B_C^2}) \tag{2}$$

Linear and quadratic dependences have been experimentally found at TJNAF and DESY [17] but only a quadratic dependence at Saclay [16] (Fig.5).

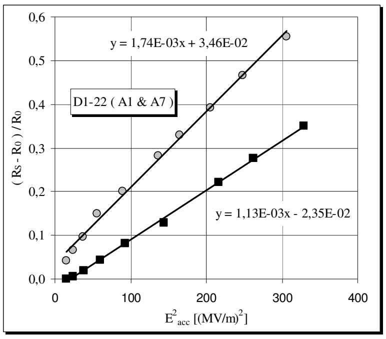

Figure 5: Quadratic evolution of the surface resistance R_S at medium field corresponding to the curves in Fig.3.

High Field Q-Drop

A refinement in the expression of the γ parameter of the precedent thermal model (equation 2) takes into account the non linear correction due the RF pair breaking [18]. This non-linear thermal model could explain both MF and HF Q-drops. But the predicted Q-slopes can not fit experimental ones at high fields [19] (Fig.6).

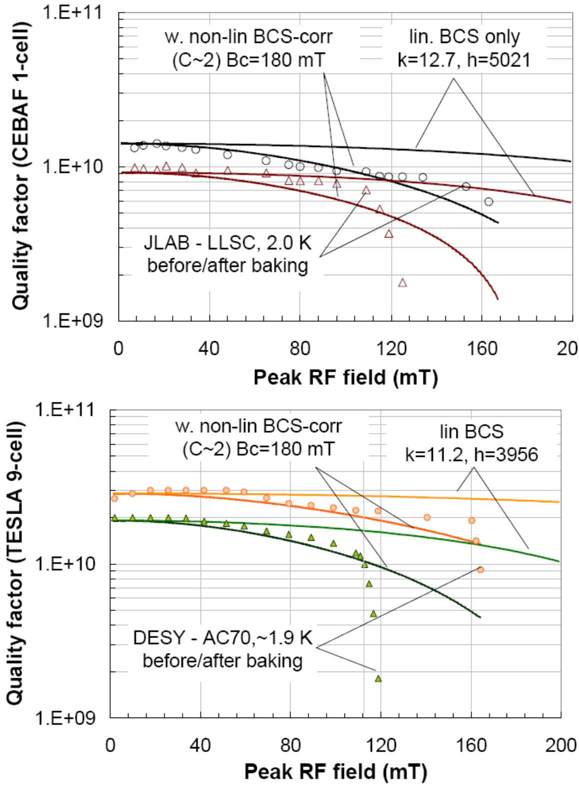

Figure 6: Results of linear and non linear thermal model. Comparisons with experimental data achieved on 1-cell cavity at JLab and 9-cell cavity at DESY.

No less than six other theories claim to explain the high field Q-slope. Descriptions of these theories and their experimental predictions have been compared to experimental observations through summary Table 1 [20, 21]. None of these proposed theories give an acceptable explanation to understand the Q-slope origin.

	Q-Slope Fit	Q-Slope before baking (EP ≡ BCP)	Q-Slope Improvem^t after baking	Q-Slope after baking (EP < BCP)	No change after 4 y. air exposure	Exceptional Results (BCP)	Q-Slope unchanged after HF chemistry	TE_{011} Q-slope after baking	Quench EP > BCP	BCP Quench unchanged after baking	Argum^t Validity	Fund^{al} Disagreem^t Exper. ≠ Theory
Magnetic Field Enhancem^t	**Y** simulat. code	~~**N**~~ $\beta_m \neq$ $B_{C2}^S \neq$	**Y** $B_{C2}^S \uparrow$	**Y** lower β_m	-	**N** high β_m	-	-	**Y** lower β_m	**N** $B_{C2}^S \uparrow$	**Y**	**D_1**
Interface Tunnel Exchange	**Y** E^8	**N** $\beta* \neq$	**Y** $Nb_2O_{5-y} \downarrow$	**Y** lower $\beta*$	**N** $Nb_2O_{5-y} \uparrow$	**N** high $\beta*$	~~**N**~~ new Nb_2O_{5-y}	~~**N**~~ improv^t	-	-	**Y**	**D_2**
Thermal Feedback	**Y** parabolic	**Y** ≅ thermal properties	**Y** $R_{BCS}\downarrow$ $R_{res}\uparrow$	**N** ≅ therm. propties	-	-	-	-	-	-	**N** C coeff.^{t}	-
Magnetic Field Dependence of Δ	**Y** expon^{tial}	**N** $B_{C2}^S \neq$	**Y** $B_{C2}^S \uparrow$	**Y** higher B_{C2}^S	-	-	-	-	-	-	~~**N**~~ thin film	**D_1**
Segregation of Impurities	**?**	**N** segregation ≠	**N** only O diffusion	**Y** surface ≠	-	**Y** good cleaning	**N** chemistry	-	-	-	**Y**	-
Bad S.C. Layer Interstitial Oxygen $Nb_{4-6}O$	**?**	**Y** NC layer	**Y** O diffusion	**N**	**N** interstitial re-appears	-	~~**N**~~ new bad layer	-	**Y** higher B_{C2}^S	**N** $B_{C2}\downarrow$	**Y**	**D_1**

Table 1: Comparison between theories and experiments (**Y**es / **N**o: **agreement** / **contradiction** between theory and experimental result; ~~**N**~~ symbolize an undisputable disagreement).

Hot spots and large grain cavity

For cavities with fine Nb grain structure, a global surface heating with a large scattering all around the equator was observed at high fields [22]. That point sustained some theories about magnetic field enhancement and segregation impurities at grain boundaries.

But, since the large grain and single crystal cavities coming, the observation is quite different. Surface heating is only located in hot spots, far from the well identified grain boundaries [23] proving thereby those are not involved in HF Q-drop.

Nevertheless, hot spots existence open the way towards a new interpretation for the Q-drop origin. Theoretically, these located sources of dissipation can be caused by defects like vortex penetration at grain boundaries, precipitates or non uniform surface oxide layer. Breakdown magnetic field reduction, non linear effect and high field Q-drop increasing are the consequences of hot spots [24].

OXYGEN DIFFUSION

Apart from the Q-drop origin, other open issue exists:

§ Why does baking remove high field Q-slope?

and its correlated question:

§ Is oxygen involved in the baking benefit?

because baking consequence is the interstitial oxygen diffusion from the oxide-metal interface towards the niobium bulk

Correlation between Oxygen and Q-slope

Some experiments are in agreement with such a hypothesis because:

§ HF Q-slope can be restored on a baked cavity by oxide layer thickening i.e. anodizing, at least 30 V, [25,26],

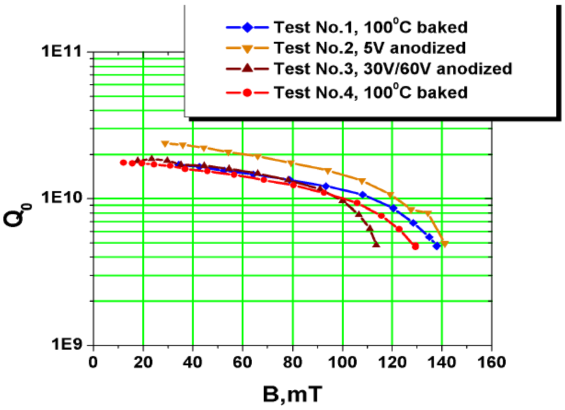

Figure 7: High Field Q-slope restoration after 30 V anodizing (red and blue data) [25].

§ "Fast Baking" method is efficient in Q-drop removal. This technique is based on the equivalence in term of oxygen diffusion between the sets of parameters: 110 °C / 60 hours and 145 °C / 3 hours [27].

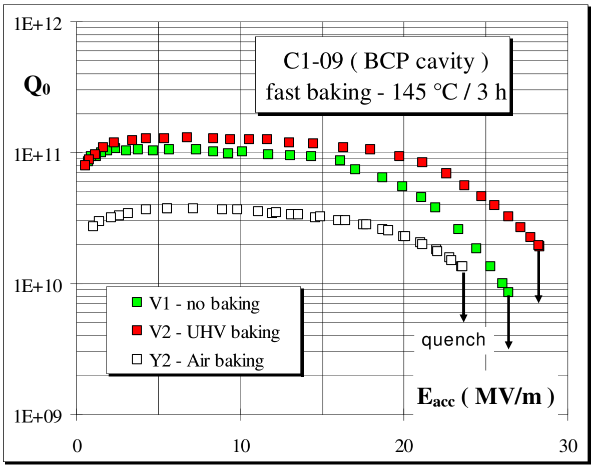

Figure 8: Improvement of High Field Q-slope after "fast baking" under vacuum at 145 °C for 3 hours (red data).

Uncorrelation between Oxygen and Q-slope

Nevertheless, a controversy point of view exists with the following experimental results arguing for the non involvement of oxygen in HF Q-drop.

For example, the high field Q-slope is not restored after forming of a new oxide layer, consequential of hydrofluoric rinse (fig.4) [16]. Similar observation can be noticed after a light anodizing (fig.7) [25].

On the other hand, strong correlations exist between RF cavity results (Fig.8) and SIMS analyses on Nb samples (Fig.9). The efficient baking with Q-slope improvement (red data) is not correlated with any noticeable interstitial oxygen diffusion. On the contrary, fast baking at the air shows an important degradation of the cavity performances, associated to a strong oxygen penetration from Nb surface [28].

Oxygen diffusion appears like a physical process to be avoided.

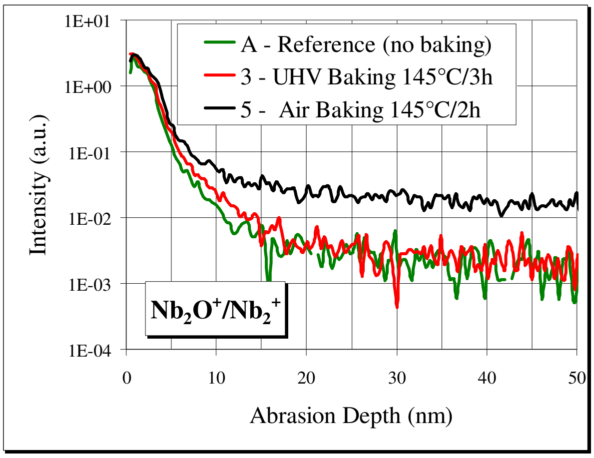

Figure 9: Interstitial oxygen profiles by SIMS analyses on Nb samples before and after fast baking (under vacuum and air atmosphere).

CONCLUSION

Concerning niobium bulk cavities, theoretical explanations of the Low and Medium Field Q-slopes are not in contradiction with experimental observations. On the contrary, the High Field Q-slope is not yet understood, even if a cure by baking exists and in spite of a lot of advanced theories and experimental data performed worldwide. Nevertheless some theories have been rejected after confrontation with their predictions; the noose for a coherent explanation is consequently tightening.

For thin film cavities, the understanding of the Q-slope and its possible cure are more sticky issues. One of the reasons is the difficulty to make allowances between specific constraints of substrate preparation and coating itself. Both stages are not yet mastered and they should be studied separately.

Niobium bulk cavity could be chosen as substrate because:

§ Chemical etching is a very "simple" way to achieve a reproducible surface preparation.

§ Characterisation of this superconducting substrate is easily carried out by RF tests.

§ Annealing at high temperature is possible as post treatment to check, for example, the influence of the hydrogen contamination during deposition.

In this way, coating parameters could be optimized efficiently. Several deposition techniques could even be compared between themselves.

For all these reasons, Nb coating on Nb substrate seems to be the way to follow to clear up thin film issues.

REFERENCES

[1] G. Müller et al., "Nb_3Sn Layers on High Purity Nb Cavities with Very High Quality Factors and Accelerating Gradients", 5th EPAC, Vol. III, WEP002L, p. 2085, Sitges - SPAIN (1996)

[2] C. Benvenuti et al., "Study of the Surface Resistance of Superconducting Nb Films at 1.5 GHz", Physica C 316, p. 153 (1999)
[3] P. Bosland et al., "Preparation and RF Tests of L-Band Superconducting Nb Coated Cu Cavities", IEEE Trans. on Appl. Superc. Vol. 9, n° 2, p. 896 (1999)
[4] V. Arbet-Engels et al., "Superconducting Nb Cavities, a Case for the Film Technology", NIM A 463, p. 1-8 (2001)
[5] S. Bauer et al., "Production of Nb/Cu Sputtered Superconducting Cavities for LHC", 9th Workshop on RF Superconductivity, Santa Fe USA (1999) - WeP016
[6] P. Bosland et al., "3rd Harmonic Superconducting Passive Cavities in ELETTRA and SLS", 11th Workshop on RF Superconductivity, Travemünde GERMANY (2003) - TuO0619
[7] C. Thomas-Madec et al., "Successful RF and Cryogenic Tests of the SOLEIL Cryomodule", 12th Workshop on RF Superconductivity, Ithaca USA (2005) - ThP45
[8] R.L. Geng et al., "First RF Test at 4.2K of a 200 MHZ Superconducting Nb-Cu Cavity", 20th Particle Accelerator Conference, Portland - USA (2003) - p.1309 - TPAB049
[9] L. Catani et al., "Cathodic Arc Grown Nb Films for RF Superconducting Cavity Applications", Physica C Vol. 441, Issues 1-2, p. 130-133 (2006)
[10] M. Sadowski et al. - *This Workshop*
[11] G. Wu et al. "Energetic Deposition in Vacuum", 10th Workshop on RF Superconductivity, Tsukuba Japan (2001) and *This Workshop*
[12] J. Halbritter et al., "RF Residual Losses, High Electric and Magnetic RF Fields in Superconducting Cavities", 38th Eloisatron Project Workshop, Erice ITALY (1999)
[13] E. Palmieri, "Q-Drop: an Analysis Starting from Elementary Fundamental Theory", 12th Workshop on RF Superconductivity, Ithaca USA (2005) - TuA02
[14] B. Visentin et al., "Improvement of Superconducting Cavity Performances", 6th EPAC, Vol. III p.1885, Stockholm - SWEDEN (1998) - TUP07B
[15] J. Halbritter, "Material Science of Nb RF Accelerator Cavities: where do we stand 2001", 10th Workshop on RF Superconductivity, Tsukuba - JAPAN (2001) - MA006
[16] B. Visentin "Low, Medium, High Field Q-Slopes Change with Surface Treatments", ICFA Beam Dynamics Newsletter n°39 (April 2006) p. 94-106
[17] G. Ciovati "High Q at Low and Medium Field", ICFA Beam Dynamics Newsletter n°39 (2006) p. 80-93
[18] A. Gurevich "Thermal RF Breakdown for Superconducting Cavities", ICFA Beam Dynamics Newsletter n°39 (2006) p. 34-44
[19] P. Bauer et al., "Evidence for Non-Linear BCS Resistance in SRF Cavities", Physica C Vol. 441, Issues 1-2, p. 51-56 (2006)
[20]- B. Visentin "Q-Slope at High Gradients: Review of Experiments and Theories", 11th Workshop on RF Superconductivity, Travemünde GERMANY (2003) - TuO01
[21]- H. Edwards, M. Liepe "Session II Summary: High Q, Field Emission, Q-Slope", Pushing the Limits of RF Superconductivity Workshop, Argonne Nat. Lab. USA (2004) p. 353
[22]- L. Lilje et al., "Electropolishing and in-situ Baking of 1.3 GHz Nb Cavities", 9th Workshop on RF Superconductivity, Santa Fe - USA (1999), Vol. I, p.74, TUA001
[23] E. Eremeev et al., "A Comparison of Large Grain and Fine Grain Cavities Using Thermometry", 10th EPAC Edinburgh UK (2006) - MOPCH176
[24] A. Gurevich, "Multiscale Mechanisms of SRF Breakdown", Physica C Vol. 441, Issues 1-2, p. 38-43 (2006)
[25] G. Eremeev, H. Padamsee, "Change in High Field Q-slope by Baking and Anodizing", Physica C Vol. 441, Issues 1-2, p. 62-65 (2006)
[26]- C. Ciovati, "Recent Developments in SRF Cavity Science and Performance", Lin. Acc. Conf. 2006 Knoxville USA (2006) - FR104
[27] B. Visentin et al., "First Results on Fast Baking", Physica C Vol. 441, Issues 1-2, p. 66-69 (2006)
[28] B. Visentin et al., "Fast Argon Baking Process for Mass Production of Nb Superconducting Cavities", 10th EPAC Edinburgh - UK (2006) - MOPCH141