Which Way to the Frontier? Novel Structures, Materials, and Fabrication Techniques

Chair: Dieter Proch, DESY

Guided discussion about "Which way to the frontier? Novel structures, materials, and fabrication techniques ". The discussion was concentrated on the five subjects as listed in table 1. Each subject was introduced by a "warm up" speaker who summarized present observations and initiated the discussion.

A) Q-slope at bulk niobium and its behaviour after moderate bake out

The present observations at different laboratories are summarized in table 2 (see end of this text). This table will be updated with new results by P. Kneisel (kneisel@jlab.org). As can be seen in the table:

- The Q-slope at high fields is reduced after moderate bake out as observed in several laboratories.
- This improvement is seen for EP and BCP polished cavities, but for EP cavities the gain in E_{acc} is more pronounced.

Several explanations were given for the Q-slope and its reduction after bake out. They are listed in table 3. Because of time reasons and of lack of enough experimental data the evidence of the different models was not discussed. But it might be interesting to see at the time of the next SRF workshop which model will be verified (and which author gets the winning bottle of Champaign).

Comments and proposals:

- Differentiate between E or H field effects by a special higher mode resonator with dominant E or H surface field in different modes.
- Measure the hydrogen depth profile on samples after bake out (will be done by Heraeus)
- The measured decrease of Rs (and thus of the mean free path of electrons) with bake out time suggests a diffusion process of gases as driving mechanism.

Table 1: subjects of discussion

Item	Understanding	Discussion
Q slope at bulk Nb - *Reschke*	?? cured by bake out	- data table - models of understanding
Multipacting - *Saito*	2 point at equator, else	- cavity shape - surface condition
Field emission - *Kneisel*	Fowler Nordheim current at particles	- EP surface - better cleaning
Quench - *Padamsee, Mueller*	Critical field	- H_{c1}, H_{SH}? - better SC than Nb
Q slope of Nb film - *Benvenuti*	Granularity? Roughness	- better coating - better SC than Nb

Table 3 Proposed explanations for the Q slope and the beneficial effect of low temperature bake out around 100 C. Authors in brackets were not present and gave explanations earlier.

Model	Proposed by
Magnetic field enhancement at surface roughness	J. Knobloch, Cornell
Electric effects at localised oxygen states	(J. Halbritter)
Thermal feed back	(E. Haebel)
Hydrogen diffusions, _-phase	Schoelz/Heraeus
Oxygen diffusion	E. Mahner
Surface stress due to oxygen diffusion	C. Antoine
Micropores filled with hydrogen	?

- The normal conducting surface resistance (at 10 K) should be measured to calculate the mean free path.
- Why does bake out at 800 C not show the benefit as observed by heating around 100 C?

B) Multipacting

Very often conditioning events in single cells are observed in KEK at E_{acc} approx. 20 MV/m (easy to process) and around 27 MV/m (difficult to process).

- Effect reappears after warm up/cool down cycle,
- Similar conditioning is observed at Milano (Parodi), TTF (at 20 MV/m) and earlier with CERN LEP resonators (at 7 - 9 MV/m at 500 MHz, 4-6 MV/m at 350 MHz).
- T-mapping localised the conditioned area on both sides next to equator.

- Simulation (Weingarten, Tueckmantel, Helsinki) describes two point multipacting across the equator of first order.
- Multipacting resonance is determined by magnetic RF-field; therefore the H field at the equator should be quoted rather than E_{acc} (B_n[mT] = 72 x f [GHz]/(2n - 1); n = 1, 2, 3.. from W. Weingarten, Proc. of the 2nd SRF Workshop, p 573, CERN, Geneva (1984)).
- Surface contamination (gases) enhance the secondary electron yield thus strengthen multipacting.
- In conclusion: conditioning around E_{acc} = 20 MV/m, 1.3 GHz is due to two side multipacting; unfavourable surface treatment (contamination by oil (?), condensed gases (avoid first cool down of equator region) is responsible for the need of heavy conditioning.
- Multicell cavities might have an unflat field profile, so that multipacting at different cells appears at different RF klystron levels, with the consequence of a much longer processing time.

C) Field emission

Field emission is due to Fowler Nordheim current (tunneling of electrons) at areas with locally enhanced electric field by particles. Several cleaning methods against particles are known:

- High pressure water rinsing: very simple and effective, but cannot remove particles below 10 µm unless the pressure is made higher than 100 bar.
- Megasonic cleaning: very effective for particles smaller than 10 µm.
- CO ice spraying
- UV light in ozone gas

A very detailed discussion of the cleaning methods is given in Kneisel's talk at SRF workshop 1995.

Comments and proposals:

- High pressure water cleaning of auxiliary components (coupler, beam lines, quadrupole, ..) is needed rather than better methods for the cavity alone,
- Field emission will limit the gradient in large scale linacs: how to clean such a complicated system?
- In situ cleaning (like HPP) should be developed further, because the environment of the accelerator might deteriorate the cleanliness (like observed at the Cornell storage ring).
- Standard cleaning with (hot) detergents was developed at Los Alamos and is very efficient. This method should also be applied at SRF (B. Rusnak et al, "Status of RF Superconductivity at Los Alamos National Laboratory", Proc. of the 6th SRF Workshop, CEBAF (1993))
- Megasonic cleaning (ultrasound at a frequency of several MHz) is a well known technique in semiconductor industry. At KEK this cleaning technique was applied to single cell cavities. The test results were not very promising. Probably a strong enough megasonic sound wave cannot be established inside a resonator by just one driver head. Nevertheless it seems worthwhile to explore this cleaning method with an appropriate effort in infrastructure (and money).
- Very clean surfaces of Nb samples (as measured by a DC scanning needle) were gained when rinsing the surface after BCP etching by continuous dilution of the acid by high purity water (i.e. without exposing the surface to air between etching and rinsing cycles). A bad RF result of a Nb resonator was reported from Cornell after just this treatment (Padamsee), however.

D) Limitation by quench

A fundamental limitation in RF superconductivity is the critical surface magnetic field. When surpassing this field, the cavity will become normal conducting and dissipate its RF energy in short time (quench). There are four different fields, which describe superconductors: H_{c1}, H_c, H_{c2} and H_{SH}. It is the belief that in RF superconductivity the superheated field H_{SH} is limiting the performance of a cavity. In this session experimental evidence for reaching H_{SH} is discussed.

Experimental data from Cornell (Ph.D. T. Hays) on Pb-Cu, Nb and Nb_3S_n were presented (see fig. 1, 2, 3): in the case of Pb H_c is clearly exceeded; for Nb a critical field of H_{SH} = 1.2 H_c could be verified. For Nb_3S_n the measured critical field in RF is below H_{SH}.

The same disappointing results for Nb_3S_n were reported from Wuppertal (see table 4).

A flat Q vs. E_{acc} was measured with Nb_3S_n (Wuppertal-CEBAF, 1.5 GHz) up to 40 mT (corresponding to 10 MV/m E_{acc}), then the Q-value dropped down up to max H = 80 mT. The low gradient RF performance was attributed to "weak links" in the Nb_3S_n layer.

Comments or proposals

- Producing a thicker Nb_3S_n film (> 10 µ) with succeeding etching to 5 µ might result in a large grain size (as compared to an original 5 µm thick film). For such a film the bad effect of weak links might be reduced.

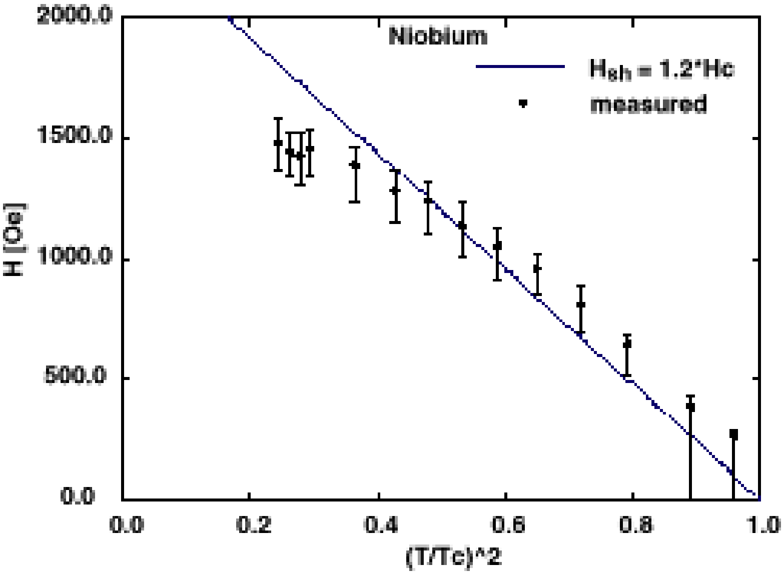

Fig 1:. Measuring the H_c^{RF} of niobium by pulsing a 1.3 GHz bulk niobium cavity of high RRR.

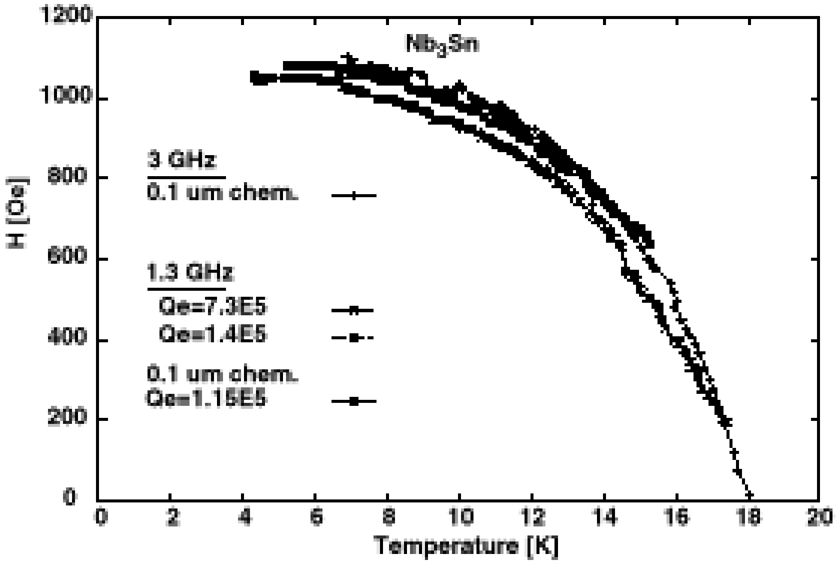

Fig. 2: Measuring the H_c^{RF} of Nb_3Sn by pulsing a Nb_3Sn coated niobium 1.3 GHz cavity and a Nb_3Sn coated niobium 3 GHz cavity. Multiple measurements were made on the 1.3 GHz cavity with different couplings and surface treatment.

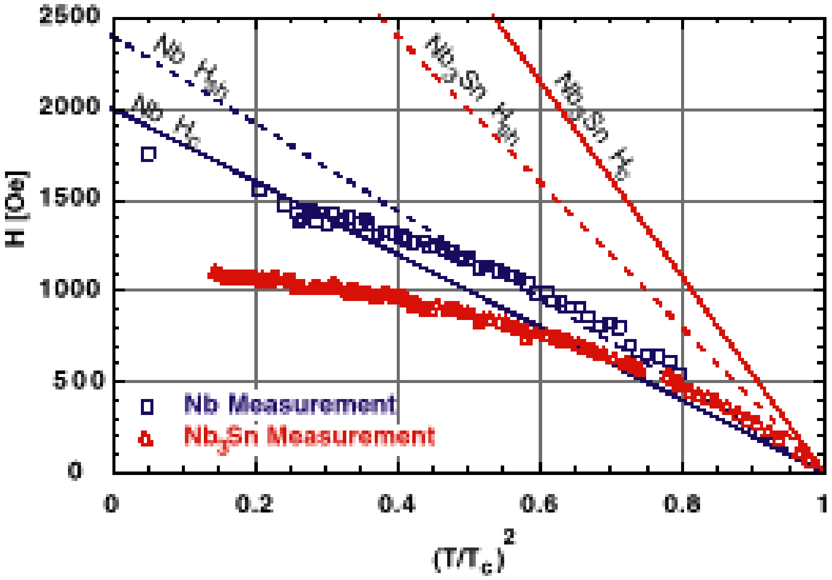

Fig. 3: Comparing the niobium and Nb_3Sn measurements against the superheating critical field predictions

Table 4: Critical magnetic fields for Nb_3S_n

H_{c1}	≤ 140 mT
H_c	= 540 mT
H_{c2}	≥ 20 T
H_{SH}	= 400 mT
H_c^{RF}, measured	80 mT (Wuppertal)
H_c^{RF}, measured	100 mT (Cornell)
H_c, weak links	≤ 50 mT

- A thicker film (> 10 µm) with larger grain size cannot be tolerated because of the low heat conductivity of Nb_3S_n.

E) Slope of Nb-Cu films

The typical behaviour of Nb-Cu films as produced in CERN is

- High Q value (higher than for Nb) at low E_{acc},
- Decreasing slope above 10 MV/m.

The subject of the discussion was, whether the Q-slope might be due to the coating method by sputtering so that other thin film technologies (chemical vapour deposition, laser ablation, Cu-evaporation, …) should be tried out.

Ch. Benvenuti mentioned the good results with Nb sputtered films on Cu resonators (see CERN Report by A.M. Valente, this workshop). Low values of $R_{S,\ BCS}$ have been gained recently (see table 5)

There is a clear correlation of surface treatment by electropolishing the Cu and low R_{BCS}. Large grains did not further improve the film performance. The role of fluxuid induced losses seems important but is not clearly proven.

Table 5: Measured surface resistance R_{BCS} at f = 1.5 GHz

	4.2 K	1.7 K
Nb film	400 nΩ	1.5 nΩ
Nb bulk	900 nΩ	2.5 nΩ

The high field performance was improved by new installations for high pressure water cleaning: maximum gradient of 22 MV/m at Q of 3 x 10^9 were measured. Nb films were not baked at 100 C, so that the possible benefit as seen with bulk Nb cavities has not been coupled?.

Open questions and comments:

- What is the reason for the very high Q at low field?
- Is there an influence of high field performance by the thickness of the film?
- At Saclay Nb films were baked at 120 C: one film improved, one film remained unchanged
- At CERN one film was baked at 300 C to get rid of hydrogen: the result was disastrous
- Other coatings:
  - At CERN the film quality was good enough for LEP cavities, so no effort was started to explore other techniques,
  - It might be important to understand the present limitations (low Q at high field) before checking new coating techniques.
- What is the penetration depth at high gradients?

Acknowledgement

The help of D. Reschke, K. Saito, P. Kneisel, H. Padamsee, G. Mueller and C. Benvenuti in stimulating the discussion is greatfully acknowledged. Special thanks are given to L. Lilje and M. Liepe for talking notes of all contributions.

Table 2: Summary of observed Q improvements after moderate (ca 100 C) bake out (compiled by D. Reschke and P. Kneisel)

Lab	Material	f [MHz]	BCP	EP	Q-slope before	Bake out $T[^0 C]$	Q-slope after	ΔE_{acc} [MV/m]	R_{BCS}	Remarks/**References**
JLab	RRR Nb	1497	yes		yes	145	↓	+ 0 - 5	↓	1-cell, 5-cell, 7-cell (several)
	RRR Nb	1300		yes	yes	145 (80)	↓	+ 0 - 5	↓	1-cell; R_{BCS} less reduced @ 80^0 C
	RRR Nb	1497	yes		yes	145	↓	+ 0 - 5	↓	seamless(spun)
	RRR Nb	1497		yes	yes	145	↓	no (quench)	↓	seamless(spun)
	Reactor	1497	yes		yes, no		↓, no	+ 2 , no	↓	seamless(spun) (2 cavities) **P.Kneisel,** this workshop
Saclay	RRR Nb	1300	yes		yes	105	↓	no (quench)	↓	1-cell (several);decrease of λ **B.Visentin et al.,** this workshop
	RRR Nb	1300	yes		yes	170	↓	+ 2 - 3	↓	**P.Charrier et al,EPAC '98,**p.1885
	Nb/Cu	1300			yes	90	↓	- 2-3 (leak)	↓	**A.Aspart et al, ASC '98**
Cornell	RRR Nb	1300	yes		yes	150	yes	- 3	↓	2-cell **J.Knobloch et al.,** this workshop
Saclay/ KEK	RRR Nb	1300	yes		yes	No				Initial test at Saclay
				yes	? / yes	85	no	+ 6 - 7	↓	R_{BCS} smaller at KEK **E.Kako et al.;** PAC '99,p.432
CERN/ DESY/ Saclay	RRR Nb	1300		yes	yes	120	No	+ 5	↓	Limited by quench (1 monocell)
				yes	yes	105	↓	+ 3	↓	2 1-cell cavities **L.Lilje et al.;** this workshop

Other observations:

- The observed behaviours are not influenced by prior heat treatments of the cavities (800 ^{0}C or 1400 ^{0}C)
- R_{res} might increase after bakeout, possibly more likely for longer times

Explanations

The following explanations for the observed improvements in high gradient behavior of the cavities following "in-situ" bake out were advanced during the discussion session (Thursday, Nov. 4, '99):

- J. Knobloch et al.: Magnetic Field Enhancement at Grain Boundaries
  this workshop
- J. Halbritter et al: Electric Field Enhancement due to Surface Roughness combined with Interface Tunnel Exchange into localized States
  To be published
- E. Haebel : Thermal Feedback TESLA Report 98-05, p. 60 ff
- Others mechanisms: suboxides (reduced H_c)
  hydrides stresses induced by oxides (lowered H_c)
- The low field behaviour after baking (lowering of R_{BCS}) can possibly be explained by changes of the material parameters such as mean free path l , penetration depth λ and Δ/ k T_c (B. Visentin et al.; K. Saito,P.Kneisel; **this workshop)**