EXPERIMENTAL INVESTIGATION OF SUPERCONDUCTING Nb DEFLECTING CAVITIES

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Abstract

Experimental results of measurements of Q-values and peak fields obtained at 1.8 K in several niobium deflecting test cavities are presented. After chemical polishing the cavities typically showed peak fields of about 250 G at improvement factors of a few 10^4. The effect of baking in an UHV-furnace or anodizing the surface was investigated but it showed no marked improvement. Fabrication techniques for the cavities and methods of surface treatment are described, and the final deflector geometry is shown. The results indicate that a superconducting RF particle separator with reasonable performance, say $E_o \approx 2$ MV/m, can be constructed.

I. Introduction

A superconducting RF beam separator is now being constructed at Karlsruhe for installation in the Omega-beam at CERN. The separator will be of the Panofsky-Schnell-type with two S-band deflectors each 2.73 m long$^{1)}$. Experiments with the 25 GeV-Proton-Synchrotron will require equivalent deflecting fields of about 2 MV/m. It is anticipated, that the same separator will remain usefull for beams from CERN-II.

In a previous paper we discussed the design problems to be expected in building a superconducting deflector and indicated the solutions which appeared promising$^{2)}$. In the meantime our work has progressed to the extent that the geometry of the deflector has been finalized. Although we have already demonstrated the feasibility of superconducting separators some time ago, an extensive test program was initiated to obtain the information necessary for the fabrication of deflectors with predictable superconducting properties. The description of this program and the experimental observations represent the main topic of this paper.

The investigation of superconducting deflectors at Karlsruhe started in 1967 with lead-plated copper cavities which were also applied for the deflection of 1 MeV electrons by a 0.5 m-long superconducting deflector$^{3)}$. Magnetic and electric peak fields of $\hat{H} \approx 200$ G and $\hat{E} \approx 7$ MV/m corresponding to an equivalent deflecting field of $E_o \approx 1$ MV/m at an improvement-factor of typically 10^4 were observed$^{4)}$. To improve upon these results, a different geometry with lower $\hat{H}/E_o$-ratio was adopted and pure niobium was selected as the superconducting material in view of its inherently smaller losses and higher critical field. Even more important advantages of using Nb lie in the possibility (1) of fabricating complex structures by electron-beam welding and (2) of improving the surface after fabrication by various techniques such as baking in an UHV-furnace$^{5)}$.

To develop the technology required in the fabrication of superconducting niobium cavities we constructed two deflectors with irises of constant thickness at Karlsruhe (K I and K II) and a series of test structures with contoured irises in cooperation with Siemens at Erlangen (S I to S V). Even though the test program is not yet completed, the results obtained sofar have yielded the information necessary for ordering fullsized deflectors. It has become clear that the main limitation is imposed by magnetic breakdown rather than by the RF losses, although occasionally, in low-Q cavities, the peak fields are limited by thermal breakdown. Multipactoring at field-levels between a few 100 kV/m and a few MV/m is also a serious problem$^{6)}$. In contrast, field emission as observed at HEPL, Stanford, seems to be negligible in our structures$^{7)}$.

The experimental program at Karlsruhe was hampered by the lack of an UHV-furnace. Through the courtesy of HEPL and SLAC we were able to bake two cavities in their furnaces and obtain some relevant information, but the vast majority of the results were obtained after chemical etching and/or heat treatment in a furnace with poor vacuum. The recently suggested method of anodizing the Nb surface$^{8)}$ has also been tried, but a definite comparison of the various methods is not yet possible. Nevertheless we thought it desirable in this paper to give all significant data collected sofar. Some conclusions on the technology of superconducting Nb can already be drawn,

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but it is obvious that conclusive statements will have to await the measurements in preparation.

II. Deflector Geometry

The various considerations entering the choice of the deflector geometry have been previously discussed in ref. 2. New aspects of the problem have induced us to modify the deflector geometry. In particular, the procurement of an UHV-furnace with a hot-zone of 20 cm in diameter and 60 cm in height made it possible to reduce the number of deflector sections from 11 to 5, leading to the new arrangement of sections respectively 19, 22, 22, 22, and 19 cells long corresponding to a total length of 2.73 m. Reducing the number of sections shortens the time required for the heat treatment and alleviates the joint problem. The questions of obtaining a good RF joints between the sections is, however, still open. In case of unsurmountable joint problems they could be circumvented by using 5 electrically isolated sections which then would preferably be π-mode structures.

Although bi-periodic or multiperiodic π-mode structures exhibit clear advantages over uniform-periodic structures, we have opted for the latter solution in view of the lack of time necessary for the design of these structures.

The dimensions of the deflector have been finalized, but it is likely that the outer diameter must be adjusted slightly to yield the correct operating frequency of 2855 ± 5 MHz at 1.8 K. The deflector geometry with the dimensions at room-temperature together with the salient deflector parameters are shown in Fig. 1. It should be noted, that the excentricity serves to completely suppress the mode degeneracy by lifting the orthogonal mode by over 50 MHz. Other solutions such as suppressor rods or elliptical cross-section were also considered, but rejected because of the difficulties of fabrication.

Coupling cell and tuning cells have a geometry with basic dimensions identical to the unperturbed cell. There is no point in changing the tuning cell considering the

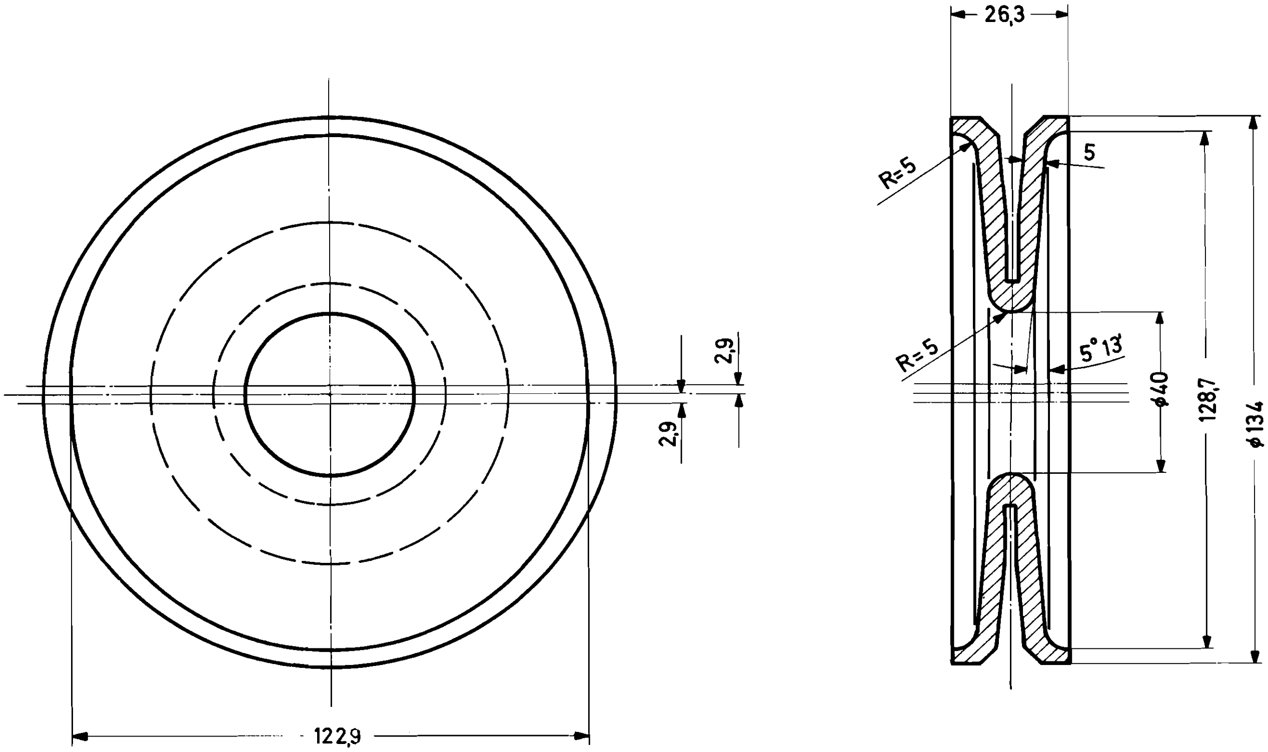

Fig. 1: Uniform-periodic deflector geometry in π/2-mode. The salient deflector parameters are $\hat{H}/E_0$ = 155 G/(MV/m), $\hat{E}/E_0$ = 5.5, R/Q = 760 Ω/m, and R = 7.6MΩ/m × improvement factor in SW operation. The excentricity splits the degenerate modes by 50 MHz.

deliberate changes by means of the tuning plunger. The frequency perturbation caused by the coupling hole seems to be desirable because this detuning reduces the otherwise excessive peak fields in the coupling cell. The coupler-induced fields at the joints are smaller than those induced by fabrication tolerances.

Ideally the deflector is terminated by end half cells. The unavoidable beam tube would, however, represent the largest systematic perturbation in the deflector and must be compensated for by a change in cell length and/or outer diameter. One possibility is to use a full end cell with smaller outer radius. It is anticipated, that this solution will not increase the risk of multipactoring.

III. Test Cavities

In order to obtain the information and to develop the technological skills necessary for the successful construction of full-sized niobium deflectors, a test program was initiated about two years ago. At the inception of this program it was hoped that the knowledge gathered on simple TE and TM resonators could be applied directly to this specific problem. But it was soon realized at this laboratory, as well as at others, that the development work has to be repeated for each particular geometry and frequency.

Among the questions which needed clarification one should mention

1) material properties: purity, grain size, grain boundaries, internal stresses,
2) surface conditions: roughness, protrusions, oxides, contamination,
3) fabrication methods: machining of smooth surfaces, coining, lathe-turning, electron-beam welds in particular EB welds of various thickness, tolerances,
4) post-fabrication improvements: electropolishing, chemical polishing, heat-treatment in UHV-furnace, anodizing, ion-bombardment, etc.

Each of the problems mentioned could easily become a project in its own right and iron-clad self-discipline must be exerted to restrict the efforts to the essential points.

In view of the pressure for rapid completion of the project the test-program is comprized of a relatively large number of cavities which has permitted the simultaneous study of various questions and the isolation of specific problems. A list of the test-cavities is given in Table I. Some remarks seem in order.

1) The cavities S I to S IIa are fabricated by EB welding of coined cups without subsequent machining. In order to avoid the weld on the iris edge, to obtain better surface finish and greater mechanical

Table I: List of test cavities

Designation	Length[a]	Joint	Beamtube	Tuner	Eccentricity	shaped iris	EB weld[b]		Material		Cooling	Completion
							ID	OD	Source (Ta in ppm)	Form (grainsize)		
K I	2	×	-	-	-	-	-	-	Kawecki (350)	billet (large)	no	Apr. 70
K II	6	×	-	-	-	-	-	×			4 channels in iris	Feb. 71
S I	6	-	×	-	-	×	×	×	Kawecki (950)	sheet (small)	2.6 mm wall thickness	Sep. 70
S II	6	×	-	-	-	×	×	×				Jan. 71
SIIa	2	-	-	-	-	×	×	×				Apr. 71
SIII	4	-	-	-	-	×	-	×	Wah-Chang (300)	billet (small)	5 mm wall thickness	May 71
S IV	4	-	×	-	-	×	-	×	Fansteel (500)			July 71
S V	12	-	×	×	×	×	-	×	Wah-Chang (300)			Oct. 71

[a] in units of $\lambda/4 = 2.63$ cm

[b] Electron-beam weld on inner diameter (ID) and outer diameter (OD)

strength, and to achieve greater flexibility in eventual dimensional adjustments it was decided to machine the final deflector from cold-forged rings with T-shaped cross-section. Because EB-melted material with large grain size always shows small voids, we decided to use cold-forged small-crystalline material for the final deflector. This material will be re-crystallized in an UHV-furnace after final machining.

2) The Ta-content of the materials used varied from 300 to 950 ppm, but otherwise the purity is supposed to be comparable (better 99.8 %).

3) The geometry of the "S"-cavities with contoured irises is similar to the final version which is preferable to the "K"-geometry because of better conditions for cooling and chemical treatments (no trapped gases).

4) Beamtubes in the end cells cause a strong perturbation of the frequency (to be corrected in S V) and field distribution but are desirable if the cavity is to be electro-polished or anodized.

5) Producing a nearly lossless RF joint still represents the most serious problem and several solutions are being investigated on S II and K II. The tolerances achievable of ± 30 μ on outer diameter and ± 120 μ on cell length may induce magnetic fields of up to 100 G in the joint cells which explains the difficulty of the joint design.

6) Tuning the cavity by means of a niobium plunger is being tested separately on a TE_{011}-cavity which was made available to us by CERN9). The eccentricity causes special problems for the EB welding. Both problems are being investigated separately, and solutions will be verified on S V.

7) Until now the cavities have not been vacuum-sealed, but a hopefully equivalent solution using cold RF windows and a pump is in preparation.

IV. Experimental Results

At the present time we have tested all cavities with exception of S V. All cavities with joints performed poorly, and it is not worthwhile to record the results. Cavity K I is being remachined and welded into a test cavity for multipactoring. Cavities K II and S II are being used for the continuing development of lossless joints. S III has been shipped to Stanford for heat treatment. Significant results have been obtained sofar on S I, S IIa and S IV and are summarized in Table II.

Most measurements follow a typical pattern10). Initially, before applying

Table II: Results on π/2-mode Nb deflector

Cavity	Date	Q_{res}	Proc.time (h)	Q_o at	$\hat{H}$(G)	treatment preceding the measurement
		$\times 10^6$		$\times 10^6$		
S I	Dec.70	1800	20	400	220	chem.polish: 60 % HNO_3 - 40 % HF & furnace: 6h at 1450°C and 10^{-5} torr
S I	Apr.71	750	7	360	210	HEPL-furnace: 3h at 1850°C and 10^{-7} torr
S I	June71	720	15	125	200	anodized in NH_3 solution at 25 V
S IIa	May 71	180	30	11*	87 147+	SLAC-furnace: 9h at 1900°C and 10^{-7} torr
S IIa	June71	360	50	290	240	anodized in NH_3 solution at 25 V
S III	Sep.71	1700	20	800	130	SLAC-furnace: 6h at 1750°C & 3×10^{-7} torr
S IV	Sep.71	410	2	380	335	chem.polish: 60 % HNO_3 - 40 % HF at -10°C
S IV	Sep.71	250	2	240	320 335+	same as previous measurement, no magnetic shield
S IV	Sep.71	2700	6	1400	300	chem.polish & anodized at 20 V

*surface contaminated during tests

+pulsed operation

higher RF power, the low-level residual quality factor Q_{res}, is highest. Improvement factors of a few 10^4 are common, the highest measured is $I = 2.7\times10^5$ in the $\pi/2$-mode. The peak field achievable is initially limited by multipactoring[6]) at values of about $\hat{E} = 0.3\div3$ MV/m. These barriers can be overcome by processing, i.e. continuous operation under this condition for a longer time. The time it takes to penetrate a multipactor-barrier depends on the previous treatment. There is some indication, although not irrefutable, that UHV-furnace-baked cavities need less processing time. Processing in the presence of some He-gas also seems to be beneficial. The barriers reappear occasionally but are then easily penetrated. Processing nearly always causes a permanent reduction in Q_{res}. In contrast, the field-dependence of the unloaded quality factor, Q_o, is of no importance up to the breakdown fields. After penetration of the last multipactor-barrier, the fields can be increased without further delay until magnetic breakdown occurs. The highest fields measured are 335 G and 12 MV/m under CW conditions. The limitations are caused by magnetic breakdown rather than field emission. In poor low-Q cavities the peak fields may be limited by thermal breakdown. In contrast to magnetic breakdown, the thermal breakdown-limit depends on the average power fed into the cavity and can be increased by pulsed operation.

The present results do not permit the dispute about degassing in an UHV-furnace versus anodizing to be settled; actually, the shortest processing time and the highest peak field were obtained with a chemically polished surface. More definite answers will have to await the availability of an UHV-furnace at Karlsruhe. It is conceivable that a combination of both methods will yield the best results. But it should be kept in mind that anodizing alone is attractive because it can be done at low temperatures avoiding the geometrical changes in the furnace (On S I and S IIa, the frequency was lowered by more than 1 MHz by the heat-treatment) and may provide an effective protection against surface contamination.

In conclusion we can state that in spite of some remaining questions we have clearly demonstrated the feasibility of superconducting deflectors as required by long-pulse RF beam separators.

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DISCUSSION

T.K.KHOE : When showing your table, you said that the cavity S-IIa was contaminated. Do you know what sort of contamination ?

H. HAHN : The contamination was caused by a dirty vacuum system.

H. HALAMA : Did the cavity S V have a joint ?

H. HAHN : No.