RF-TESTS ON DEFLECTING CAVITIES FOR A SUPERCONDUCTING PARTICLE SEPARATOR

W.Bauer[+], A.Citron, G.Dammertz, H.C.Eschelbacher[x], H.Lengeler[*], H.Miller, and E.Rathgeber
Universität und Kernforschungszentrum Karlsruhe
Karlsruhe, Germany
and
H. Diepers
Forschungslaboratorium Siemens AG, Erlangen
Erlangen, Germany

Summary

A superconducting S-band RF particle separator is under construction which will be used at the CERN 300 GeV proton synchrotron. It is foreseen to separate particles up to at least 30 GeV/c momentum. We give a summary of quality factors- (Q) and peak magnetic field (H_p) measurements on several test-deflectors. A sequence of surface treatments including electropolishing, anodizing and an UHV-annealing around 1850°C allowed us to obtain in a reliable way Q- and H_p-values well above our minimum requirements (5×10^8 and 310 Oe respectively). The highest values hitherto obtained for the (high-field) Q and H_p are 4.3×10^9 and 510 Oe corresponding to a mean deflecting field of 3.3 MV/m. The effect of repeated cooling cycles under vacuum and exposure to clean air or methanol was found not to be critical for our range of Q and H_p. The surface resistance depends linearly on an external dc-magnetic field whereas the dependence on the RF field level is much more complicated. With our surface treatment and our deflecting modes multipacting presents no problem. Breakdowns are nearly always caused by magnetic fields. The frequency tuners foreseen are described. Fine and coarse tuning will be done by separated tuners. They have been tested successfully up to Q-values of 10^9 and peak fields of 390 Oe. Finally a computer program has been written allowing the calculation of multiperiodic deflector modes. An exemple is shown and compared with a π-mode for uniform periodic structures.

I. Introduction

At Karlsruhe a superconducting RF-particle separator is under construction which will be used at the CERN 300 GeV proton synchrotron. It has to be installed in a separated particle beam foreseen for the big counter system Omega and it is expected that a gain in detected K^--, K^+- and $\bar{p}$-intensity of at least 10 with respect to an unseparated beam will be possible.[1] The separator will be operated at S-band frequencies (2855 MHz); its two uniform-periodic niobium-deflectors will work in a π/2-mode and will have an effective length of 2.73 m, corresponding to 104 cells. The intercavity distance will be 90 m allowing, with a mean deflecting field of 2 MV/m, separation up to 30 GeV/c. This range could be extended to 40 GeV/c if deflecting fields of 4 MV/m could be obtained, (corresponding to a peak magnetic RF field of 610 Oe and a peak electric field of 22 MV/m). In order to avoid thermal breakdowns an unloaded Q-value of at least 5×10^8 has to be reached for deflecting fields of 2 MV/m.

Several test-deflectors have been designed, constructed and tested during the two past years.[2,3] This experimental program allowed us to fix by now all important parameters, the fabrication and welding techniques and the surface treatments to be applied. After the excellent performance of the test-deflectors, we decided to start the fabrication[**] of the first 3m deflector which is due to arrive in March 1973. Its cells are machined out of solid niobium[++], then welded together around the outer diameter. The mode degeneracy typical for deflector modes (dipole-modes) has been avoided by an elliptic inner cross-section.[2] Each 3m-deflector will consist of 5 sections of about 60cm length which will be joined together at the position of a field free cell. The length of the sections is limited by the requirement that prior to their mounting a thermal treatment in our UHV, high-temperature furnace with a useful volume of 20cm diameter and 60cm length has to be applied.

II. Measurements on test deflectors

In Table 1 we summarize some results. From these measurements on separator structures we conclude:

1. The application of a high temperature annealing is absolutely essential in order to obtain the required Q-values and peak fields in cavities with welded joints and complicated geometry. No satisfactory results were obtained before a firing in a high-temperature furnace. Wether a temperature as high as 1850°C or vacua of the order of 10^{-9} Torr are essential is not yet clear. A repeated application of a high temperature annealing tends to increase markedly Q_0 but only slightly H_p.
2. The high-temperature annealing (HTA) has to be combined with an electropolishing[4] (EP) treatment. Our most successful surface treatment uses two sequences 'EP-HTA'. A first EP of 10-25 µm cleans the niobium surface for the following HTA, hopefully without etching along grain boundaries as it might happen in chemical treatments. The first HTA is supposed to remove internal stresses and solved gases, especially in the region of welded joints, and improves the quality of the next EP. This second EP of ~75 µm removes the damage layer resulting from machining. As no good and reliable results were obtained after this step, a second HTA is applied, generally preceded by an anodizing of the niobium surface of 300-1000 Å thickness. This anodizing is suggested by P.B.Wilson[5] in order to reduce the carbon-content of the niobium during the following HTA. After this the deflector is connected to its UHV pumping system and all auxiliary devices are mounted. The handling is done as much as possible under clean air in order to avoid as much as possible dust

[+] present address, BNL, Upton, N.Y. 11973
[x] now at Bundesministerium für Forschung und Technologie, Bonn
[*] on leave of absence from CERN, Geneva

[**] at Siemens AG, Erlangen, Germany
[++] from Wah Chang, Albany Corp.

Table 1: Measurement Results for some Test-Deflectors (2855 MHz; T <1.8 K)

Q_o(low power) $\times 10^6$	Q_o at H_p $\times 10^6$	H_p(Oe)	Multipactor	Treatment
S IV, 4 cells				
2900	1400	470	5 h	anodized, 2h at 1850°C and 10^{-8} Torr
1750	1440	475	10 h	after preceding treatment and 8 cooling cycles under vacuum
1530	1570	485	7 h	after preceding treatment and slow exposure to clean air
1350	960	505	10 h	after preceding treatment and rapid exposure to lab.air
7400	4300	495	1 h	20 µm electropolished, anodized, 2h at 1850°C and 10^{-8} Torr
1800	2180	435	1 h	anodized, 20h at 1850°C and 10^{-8} Torr, then exposed for 2.5 h to methanol
S V*, 12 cells				
450	405	250	10min	anodized, 30h at 1950°C and 10^{-8} Torr
1000	580	220	10min	anodized, 10h at 1850°C and 2×10^{-9} Torr
S VI, 6 cells				
290	500	>300	1 h	20h at 1850°C and 4×10^{-7} Torr
1500	290	380	no	anodized, 24h at 1800°C; 1h at 1850°C, 10^{-9} Torr
1000	324	425	no	anodized, 22h at 1850°C and 10^{-9} Torr
S VII, 4 cells				
1000	610	230+	no	treatment see text
1800	1300	230	no	treatment see text
S VIII, 4 cells				
380	350	-	1 h	treatment see text
1000	900	270+	no	treatment see text

*three times rewelded because of vacuum troubles and material problems

+low H_p probably due to bad roundings

particles entering the cavity.

3. With the treatment described above and our deflecting modes we had practically no multipacting problems. The multipacting appearing in test-deflector S IV can be explained by the fact that this deflector has very slim end-cells (half-cells) favoring multipacting. In the next deflectors this problem was avoided by widening the end-cells by 5mm and correcting the influence of this widening and the influence of the beam tubes by a decrease in the outer diameter.

4. As far as we could observe, breakdowns nearly always are caused by magnetic fields.

5. The surface resistance (which in our temperature range is essentially the residual resistance) was found to depend in many ways on the RF field level. Two of the most frequent behaviors are shown in Fig.1 and Fig.2. A behavior similar to the one from Fig.1 has been found by various authors.[6,7]

6. One cavity (S IV) has been submitted repeatedly to several cooling cycles, keeping it continuously under high vacuum. The result of one of these tests is given in Table 1 and shows that with 8 cooling cycles over a period of 2 1/2 month only the low field quality factor has decreased to 60% of the initial value, whereas the high field Q-value and H_p did practically not change. An increase in multipacting time is observed. Exposures to clean air for some days and/or methanol for some hours did reduce the high-field Q_o-values but not below 10^9 and did not affect substantially the magnetic peak fields. This differs from results obtained by various authors[8,9] where a quite heavy degradation of Q_o is found. One exposure to normal laboratory air without any precautions for dust did reduce the Q_o-value below 10^9 but again did not affect H_p. From these results we conclude <u>for our range of Q_o and H_p</u> that, once a deflector shows good performance, Q_o and H_p are not reduced by exposures to air to a point intolerable for our requirements.

7. The application of a homogeneous external magnetic field parallel to the cavity axis does not affect the peak fields of H_p ~500 Oe reached but increases the residual surface resistance in the way shown in Fig.2. These results are fully reproducible. There is a linear dependence between the additional (residual) surface resistance and the applied external field which is different from the results quoted in ref.6 but agrees with results from ref.10.

III. Frequency Tuner

In a two-cavity RF-separator the two deflectors have to be operated at the same frequency. We intend to lock the generator frequency to the eigenfrequency of one deflector and the second deflector has to be tuned well within its bandwidth to the generator frequency. There is not much point to push the difference in eigenfrequencies below ± 200 kHz because the annealing at high temperatures introduces changes in the eigenfrequency of this order of magnitude. (Contrary to our expectations these changes seem not to decrease after some annealing cycles!) Pretuning (coarse tuning) of a deflector is obtained by using, as studied in ref.11, two superconducting plungers introduced to an adequate depth into a deflector cell. They are situated in a symmetric way along the deflector in order to minimize the perturbations they are producing in the (field free) joint cells. The final positioning in depth is done once the deflector is at its working temperature of 1.8°K and two conditions must be fulfilled; the right frequency has to be obtained and the quality factor has to be made a maxi-

mum or the field inside the joint cells a minimum. This should not influence H_p because there is practically no change in the field amplitude of the field-full cells as has been predicted by theory and shown in model measurements. The mechanical design is shown in Fig.3. The plunger has been made an RF-filter by a periodic change in diameter along its length, and an attenuation of ~40 dB over two periods has been achieved. The frequency response of a plunger has been calculated and determined experimentally in an 8 cell-deflector. It corresponds for a 104 cell-deflector to $\Delta f/\Delta h$ = 40 kHz/mm (h: depth of penetration) and is linear over a range of 12mm, allowing a tuning range of at least 500 kHz. The positioning can be easily done with a precision of 50μm or ± 2 kHz.
Fine tuning is achieved by a similar tuner whose end-section has a diameter of only 1.2 mm. In order not to push the requirements for speed and precision of this tuner too high, we decided to work with strongly overcoupled deflectors reducing the quality factors to $Q_L = 5\times10^6$. This corresponds to a bandwidth of 550 Hz. The moving during operation is achieved with the help of a step motor situated outside the deflector cryostat, the precision of positioning is 50μm, corresponding to ± 25 Hz. The step motor is actioned as soon as the phase error (or eigenfrequency change) exceeds a given value e.g. 20% of the bandwidth. With this device only a digital regulation is possible insuring that the frequencies of the two deflectors correspond within one bandwidth. Deviations beyond this limit are corrected with the help of an electronic phase- and amplitude regulation system. The time constant of the mechanical system evidently is rather big. We aim at 0.1 sec. However, we think that this is sufficient because all frequency changes which might be fast are small. The biggest ones are due to pressure changes in the He-bath. With a pressure regulation system allowing Δp < 0.1 Torr, which is easily achieved, the frequency variations should remain below 12 Hz i.e. well within a bandwidth of the loaded deflector.

The two types of tuners have been tested experimentally on test-deflectors with high quality factors and magnetic peak fields. For the fine tuner no influence on the Q_0-values have been found and no magnetic or thermal breakdowns have been experienced up to at least H_p = 275 Oe and $Q_0 = 10^9$. The tuner for pretuning worked without any trouble up to peak field levels of 390 Oe at a Q_0 of 290×10^6. For these tests both niobium-tuners were electropolished and annealed in the same way as our test-deflectors. A more detailed discussion of the tuners can be found in ref.12.
One can show that the cooling of the plunger would be a problem if one had to rely on the thermal conductivity of the niobium alone. Therefore a hole along the axis has been foreseen which allows cooling by superfluid helium. With a magnetic field of 500 Oe at the tip of the plunger we estimate a temperature difference over its length of ΔT < 0.001°K at the working temperature of 1.8°K.

IV. Multiperiodic Structures

As is well known the use of multiperiodic structures in standing wave superconducting accelerator or separator structures offers an elegant possibility of combining the relative advantages of $\pi/2$- and π-modes in uniform periodic structures. The shuntimpedance of multiperiodic structures can approach the one of a uniform π-mode whereas the mode spacing (or group velocity) lies in the range of $\pi/2$-modes. The number of field-full cells can be made for a given structure length nearly as low as for a π-mode, considerably reducing the machining cost of a structure. The advantage of field-free cells for joining different sections of a long structure remains. Finally it is hoped that the use of very thick disks which according to ref.13 is necessary for low H_p/E_0 can be considered without the danger of enhancing unduly multipacting. In the field of RF particle separators the use of multiperiodic structures will become even more stringent once there arises the need, for high energy separation, to use C-band or even X-band frequencies. The cell-length and disk thickness for $\pi/2$-modes at these frequencies would cause serious concern for machining and surface treatments. Therefore we have started investigations in multiperiodic deflector structures and generalized the method for computing uniform periodic structures[14] to multiperiodic structures. A computer program has been written which achieves field-matching by minimizing the difference of field components along boundary surfaces (cylinders or planes) with any periodicity.[12]
In Fig.4 we show the geometry and the corresponding dispersion diagram for a multiperiodic structure having 6 cells per period. Although this structure has not been optimized its parameters are already approaching the ones of a uniform π-mode structure:
$R/Q = 9.1\ \Omega/\text{cm}$; $v_g/c = -0.017$; $Q(Cu) = 13200$.
For a π-mode structure of equal disk-opening one gets:
$R/Q = 11.5\ \Omega/\text{cm}$; $v_g/c = 0$; $Q(Cu) = 15660$.
Normally frequency gaps (stop bands) are found in the dispersion diagram of multiperiodic structures at all $s\times\pi$-modes ($s = 0,1,\ldots$). The geometry of Fig.4 has been choosen specifically to close the gap at $k_zL = 5\pi$ (k_z: wave number, L: period length). At this point we get for the phase velocity, $v_\phi = c$. Closing all other gaps has been achieved because all cell-frequencies have been choosen equal. In near future we intend to apply this computer program to the optimization of deflector structures for higher particle energies and to combine it with a calculation of E_p/E_0 and H_p/E_0 for rounded disks.

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References

[1] A.Michelini, and G.Petrucci; Report CERN NP 72-13 (1972)

[2] W.Bauer, A.Citron, G.Dammertz, H.C.Eschelbacher, H.Hahn, W.Jüngst, H.Miller, E.Rathgeber, and H.Diepers. Proc.Conference High Energy Accelerators, CERN 1971, p.253

[3] W.Bauer, A.Citron, G.Dammertz, H.C.Eschelbacher, W.Jüngst, H.Lengeler, H.Miller, E. Rathgeber, and H.Diepers. Proc.Applied Superconductivity Conference, Annapolis, Maryland 1972, p.653

[4] H.Diepers, O.Schmidt, H.Martens, and F.S.Sun Physics Letters 37A, 139 (1971)

[5] P.B.Wilson. private communication

[6] P.B.Wilson, M.A.Allen, H.Deruyter, Z.D.Farkas, H.A.Hogg, E.W.Hoyt, H.L.Martin, and M. Rabinowitz. Proc.Conference High Energy Accelerators, CERN 1971, p.237

[7] P.Kneisel, O.Stoltz, and J.Halbritter. Proc. Intern.Conference on Low Temperature Physics Boulder, Colorado, 1972; in press

[8] P.B.Wilson. Proc.Conference on Proton Linear Accelerators, Los Alamos 1972, p.82

[9] H.J.Halama. Proc.Conference High Energy Accelerators, CERN 1971, p.242

[10] E.Piosczyk, P.Kneisel, O.Stoltz, and J.Halbritter. This Conference

[11] D.Corlé, D.Leroy,and P.Morignot.Report CERN/MPS-MU/SD 70-2 (1970)

[12] G.Dammertz, Dissertation Karlsruhe 1973; to be published as KFK-Report, Karlsruhe 1973.

[13] V.Vaghin. CERN-Report 71-4 (1971)

[14] W.Bauer, and H.Hahn. Part.Accelerator 3, 193 (1972)

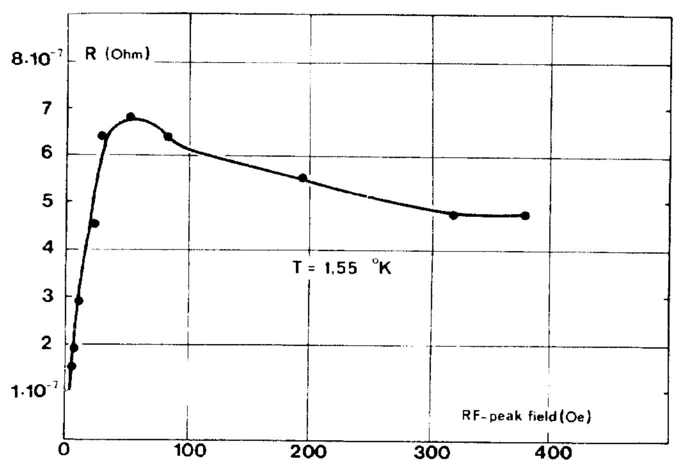

Fig.1: Surface resistance as a function of hf-field strength in S VI. Surface treatment: anodized, annealed for 24h at 1800°C and for 15h at 1850°C and 10^{-9} Torr.No multipacting.

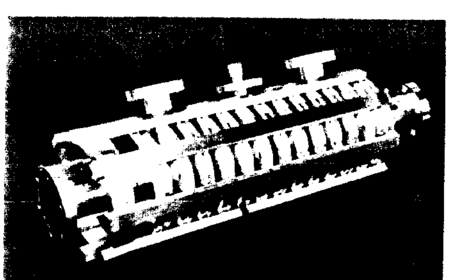

Fig.5: Photography of a 12 cell Nb-test-deflector(SV) with radial input and output coupling tubes, a tuner tube and two beam tubes. The deflector is reinforced by Nb-bars.

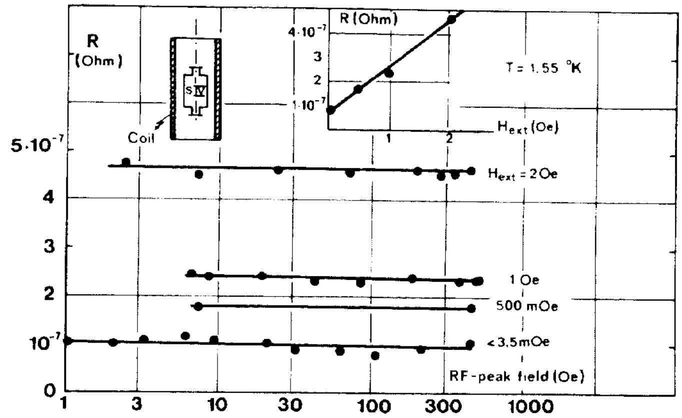

Fig.2: Surface resistance of S IV as a function of hf-field strength with an external magnetic dc-field applied above T_c and during experiment. Homogeneity <1%, earth-field shieldel to <3.5 mOe. Surface treatment: anodized,annealed for 30h at 1850°C and 10^{-9}Torr;some hours of multipacting. Insert: Dependence of surface resistance on external magnetic field.

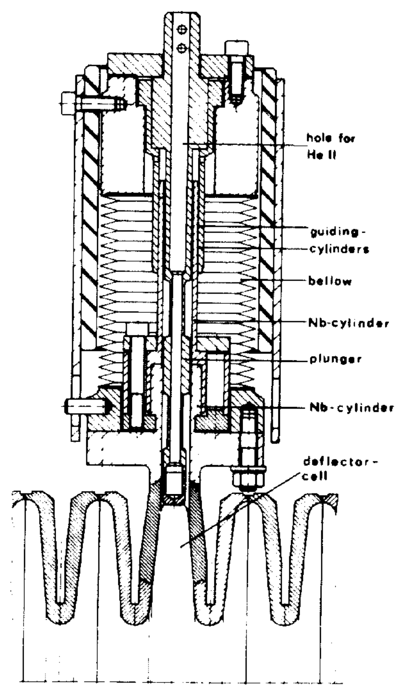

Fig.3: Mechanical layout of the tuner system with plunger for pretuning. The plunger for fine tuning has a similar layout with an endsection of 1.2mm diameter.

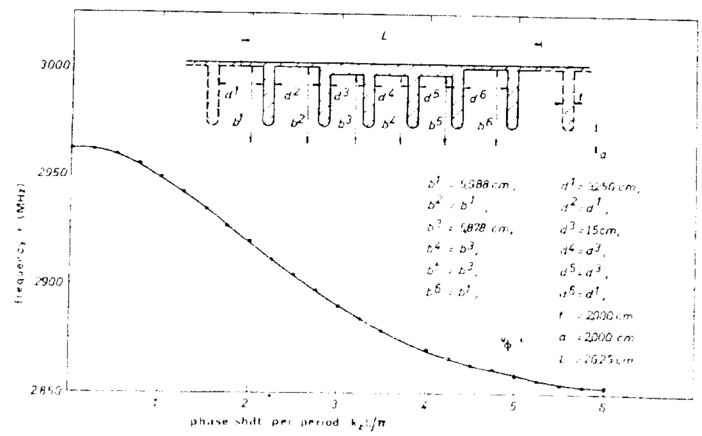

Fig.4: Dispersion diagram for the multiperiodic structure shown.