SUPERCONDUCTING NIOBIUM DEFLECTORS*

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Summary

The study of S-Band superconducting niobium cavities is being carried out for application to long-pulse rf beam separators in the momentum range of the AGS, whereas, X-Band frequencies are being considered for the NAL accelerator. Results for a 5-cell S-band prototype are: a peak field of 410 G, corresponding to an equivalent deflecting field of over 2 MV/m, and a loss improvement factor of 2 x 10^5. The fabrication and post-fabrication treatments are described. Perturbation measurements to determine deflector parameters are summarized. A new type of mode stabilizer is suggested. A 7-cell X-Band deflector is under construction.

1. Introduction

The study of rf superconductivity has the potential application to rf separators for counter experiments which require the separator to be operational for several hundred milliseconds.[1] Estimates of particle fluxes for the Multi-Particle Spectrometer facility now under construction[2] indicate that long-pulse superconducting separators would be desirable, but lack of funds postponed the actual construction of a separated beam.

The design of the BNL separator[1-4] assumed three 2.5-m long deflecting cavities operating at 2.855 GHz (S-Band) and capable of an equivalent defelection of initially E_0 = 2 MV/m and later on 4 MV/m. A 5-cell test cavity was designed and fabricated. This BNL test cavity closely resembles the Karlsruhe cavity S IV.[5-7] Long-pulse rf separators are also of interest to NAL. To obtain a realistic basis for a design, we have fabricated an 8-cell test deflector operating at 8.66 GHz (X-Band). Results are forthcoming.

2. Design of Deflecting Structures

Design of a superconducting separator is a compromise involving shunt impedance and tolerable peak fields on one side, and mechanical tolerances and rf joint problems on the other. The operating frequency, geometrical parameters and operating mode, must all be given careful consideration.

Because of the rapidly increasing intercavity distance with higher momenta, shorter wavelengths are preferred. For a superconducting structure, the question still is open, whether higher frequencies might yield a better performance or not. For reasonable apertures and technically possible structures, one would scarcely exceed a frequency of about 9 GHz.

Several authors[8,9] pointed out the advantages of iris apertures larger than those presently used. At X-Band the problem of alignment of the cavities can be solved more easily. Remachining the electron beam welds would be possible. However, shunt impedance and peak field ratios become worse; whereas, fabricating tolerances become less severe. The problem of introducing unwanted modes does not limit the choice of aperture.[10]

At X-Band the higher shunt impedance, lower peak fields, more convenient iris thickness and iris distance favors the π-mode. Unexcited cells required for rf joints between sections are obtained by omitting irises,[11] leading to a π-like multiperiodic structure (Fig. 1).

Properties of various deflectors were calculated using equivalent circuits[12,13] and are compared in Table I. The values for shunt impedance, Q and peak fields are taken from Ref. 14. $\varepsilon_i = \Omega_i/\kappa$ is the rms value of the individual cell errors. For the deflectors shown, reasonable numbers for $\bar{\varepsilon}_i$ are 0.01 for the $\pi/2$-mode, 0.016 for the π-mode at S-Band and 0.05 for the π-mode at X-Band, which result from cavity diameter tolerances of 25 μm. The quantities i_1, i_2, i_3 shown are the currents across the first, second, and third joint, normalized to the current in the excited cells.

Pretuning the single sections, for instance, by electropolishing them all to the desired frequency, may result in deviations $\varepsilon^m = \varepsilon^I,\ldots\varepsilon^V$ from this frequency. $\bar{\varepsilon}^m = 10^{-3}$ implies that the single sections are pretuned to approximately 30 kHz within the desired frequency of 2.855 GHz.

Table I shows that the joint currents of the multiperiodic π-mode structure are of the same order of magnitude as in the $\pi/2$ mode. One concludes that a multiperiodic structure of 2.32 m length gives a slightly smaller deflection than a $\pi/2$ structure of 2.73 m, but has a smaller cryostat and half the number of cells and electron beam welds. The possibility of multipactoring is reduced by the larger distance between the irises.

3. Mechanical Design and Fabrication

The niobium test deflector (Fig. 2) fabricated at BNL is similar to the Karlsruhe deflector S IV, but modified to fit our standard measuring set-up. The X-Band deflector was designed to avoid impractically thin irises (Fig. 3).

Solid billets of electron-beam-melted reactor-grade niobium, were rough machined with high speed tool steel and finish machining was accomplished with "Everede" C_2 tungsten carbide tool inserts using cutting parameters of 1-2 mil deep, 0.5 mil feed/revolution, and surface speed of 100-120 ft/min. A smooth top rake with no chip breaker was essential. Freon 113 was used as a coolant. A finish of 8-12 μin. was obtained.

Electron beam (EB) welding was used for all joining. Beam parameters depend on the filament used; therefore, a sample was run prior to welding a cavity.

Unavoidably, EB welding causes some distortion; typically, the S-Band deflector end plates were out of parallel by 9 mil and the circumferential weld caused an axial shrinkage of 5 mil per joint. To minimize this effect, pieces for the X-Band cavity were heat treated at 1400°C for 5 hours prior to final machining, ensuring also stress relief and grain growth.

The X-Band cavity is being welded and assembled such as to allow the circumferential welds in the 3 rf excited cells to be machined smooth on the inside surfaces after welding.

Both test cavities were machined without mode stabilizers. The perturbation due to coupling ports removes the degeneracy completely. Actual deflectors, however, require mode stabilizers and the use of eccentric structures[6,15] is being considered. An alternative solution which appears simpler to fabricate is here suggested (Fig. 4). An aluminum model was machined and rf tests indicate a splitting of the degenerate dispersion's curves by 46 MHz.

The final mechanical surface finish of the S-Band cavity was obtained by tumbling[16] for 45 hours using crushed and sieved Almco tumbling media 114 P in a solution of 500 cm^3 distilled water, 5 cm^3 Almco 2220 cleaning compound and 10 cm^3 of Almco 408 silica flour. A surface finish of 8 μin. was achieved after tumbling the cavity 4 separate times for 6 hours at 70 rpm.

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TABLE I - Comparison of Various Deflecting Structures

Mode (Frequency, GHz)	$\pi/2$ (2.855)	Multiperiodic* (2.855)	Multiperiodic* (8.6)
Overall length, (cell† length), cm	273 (2.625)	232 [347] (5.25)	229 [343] (1.73)
Number of cells, end sections	2 x 19	2 x 5½	2 x 16½
Number of cells, middle sections	3 x 22	3 x 11 [5 x 11]	3 x 33 [5 x 33]
Iris thickness (iris diameter), mm	10 (40)	20 (40)	6.7 (13.3)
Field ratios $\hat{H}/E_o$, G/MV m^{-1} ($\hat{E}/E_o$)	158 (5.6)	118 (3.3)	118 (3.3)
$\hat{H}$ (G), (E_o, MV m^{-1})	400 (2.53)	400 (3.40)	400 (3.40)
Transverse momentum per deflector, MeV/c	7.0	6.4 [9.6]	7.3 [11]
$(R/Q)_{theory}$, Ω/m (Q_{theory})	848 (10 300)	1150 (15 660)	348 (9000)
Improvement factor	5×10^4	5×10^4	10^5
Power per deflector, W	25	15 [22]	7.9 [12]
Currents at joint (not pretuned):			
i_1	5.5 $\bar{\varepsilon}_i$	3.9 $\bar{\varepsilon}_i$ [4.0 $\bar{\varepsilon}_i$]	7.2 $\bar{\varepsilon}_i$ [7.5 $\bar{\varepsilon}_i$]
i_2	7.0 $\bar{\varepsilon}_i$	5.7 $\bar{\varepsilon}_i$ [6.4 $\bar{\varepsilon}_i$]	13.7 $\bar{\varepsilon}_i$ [11.7 $\bar{\varepsilon}_i$]
i_3		[7.1 $\bar{\varepsilon}_i$]	[13.4 $\bar{\varepsilon}_i$]
Currents at joints (pretuned):			
i_1	18.4	17.7 $\bar{\varepsilon}^m$ [17.9 $\bar{\varepsilon}^m$]	61 $\bar{\varepsilon}^m$ [77 $\bar{\varepsilon}^m$]
i_2	24.5	32.4 $\bar{\varepsilon}^m$ [35.5 $\bar{\varepsilon}^m$]	111.4 $\bar{\varepsilon}^m$ [109.5 $\bar{\varepsilon}^m$]
i_3		[41.5 $\bar{\varepsilon}^m$]	[111 $\bar{\varepsilon}^m$]

* in brackets [ ]: version with 7 sections.

† 1 cell = ¼ wavelength in $\pi/2$, ½ wavelength in π-mode.

4. Perturbation Measurements

Parameters such as interaction impedance R/Q and surface field values of $\hat{H}/E_o$ or $\hat{E}/E_o$ are determined by room temperature perturbation measurements, using aluminum models.[17] The aluminum model is identical to the niobium cavity (Fig. 2), with the exception of added mode stabilizing rods. We find that in the $\pi/2$-mode, the peak magnetic field occurs on opposing points on the two center irises, and has a value of $\hat{H} = 14.6 \times 10^{-3} \sqrt{PQ}$, where $\hat{H}$ is in gauss and P is in watts.

Again using perturbation techniques, we find for the proposed S-Band deflector the parameters R/Q = 760 Ω/m, $\hat{E}/E_o = 6.17$ and $\hat{H}/E_o$ = 161 G/MVm^{-1}. Figure 5 is a plot of both E/E_o and H/E_o over the surface of the iris, along a path where these two quantities become maximum.

5. Results

The rf fields in a superconducting cavity penetrate to a depth of only several hundred angstrom. Surface imperfections, such as roughness, EB welds, grain boundaries, impurity inclusions, etc. greatly influence the losses and peak fields obtainable. To achieve a desirable clean smooth surface, we employed the following techniques:

a) Tumbling (already described in Section 3).

b) Chemical polishing in a solution of 40% hydrofluoric and 60% nitric acid at about 0°C. The removal rate depends on temperature and is about 25 μm/min. Since the solution heats up rapidly, larger removals are carried out in 20-30 sec steps.

c) Electropolishing[18] in a solution of sulphuric and hydrofluoric acid at 9-15 V produces a smoother surface with less etching at grain boundaries, but requires a very stable (0.1%) high current power supply. A controlled removal rate of 1 μm per oscillation train can be used to adjust the resonant frequency of individual deflector cells.

d) Firing in UHV furnace at temperatures of 1800-2000° C and pressures of 1-5 x 10^{-8} torr.

To date, rf superconducting tests were performed on the S-Band cavity. After fabrication, the cavity was chemically polished and heated for 1 hour at 2000° C and 5 hours at 1850° C. Initially, the Q was only 10^8 and electron loading limited the peak field to 30 G.

The cavity was then refired in the UHV furnace, resulting in a Q of 2.2 x 10^8, but the peak field was again limited to 59 G by electron loading. After about 3 hours of running (processing by driving the cavity with rf power) the electron loading was overcome and a peak field of 365 G was achieved. Further heat treatment in the UHV furnace increased the Q to 2 x 10^9 but failed to increase the peak field.

After a total of 5 heat treatments, 2 chemical polishings and one electropolishing the Q degraded to about 2 x 10^7. Neither firing, polishing nor rewelding was able to restore the deflector to its previous level of performance.

The deflector was then tumbled (see above), followed by a 20-sec chemical polishing and firing for 50 min at 2000°C and 4½ hours at 1850°C with a final pressure of 1.8 x 10^{-8} torr. The above treatment produced the best results, namely Q_{res} = 1.4 x 10^9 and Q_o = 0.88 x 10^9 at $\hat{H}$ = 410 G. Subsequent firing again improved the low level Q_{res} to 3.7 x 10^9, but did not increase the breakdown field.

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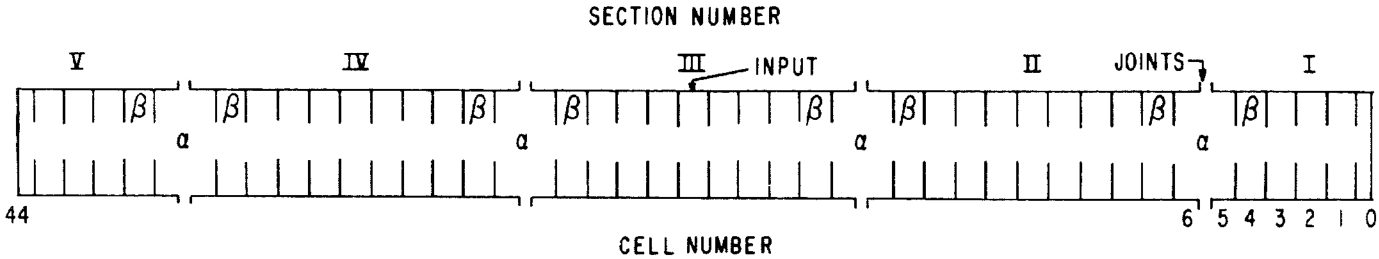

Fig. 1. Five-section multiperiodic deflector.
α cell adjusted to close gap in dispersion curve,
β cell adjusted to minimize joint currents.

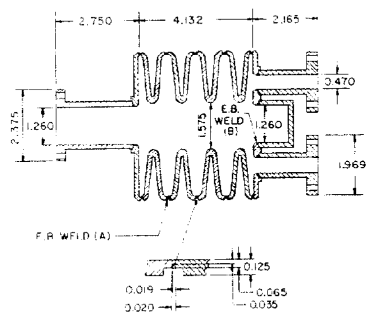

Fig. 2. S-band niobium test deflector (2.86 GHz, $\pi/2$ mode).

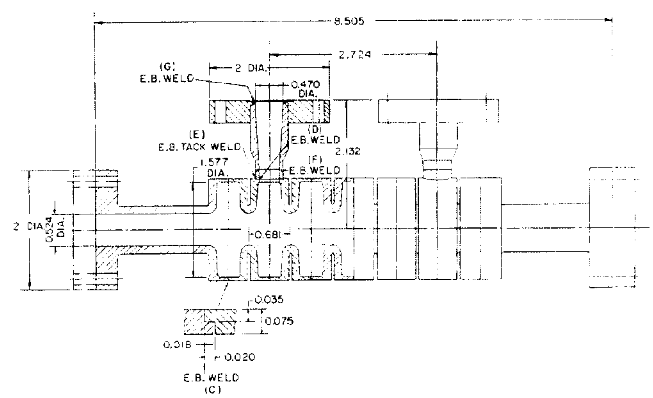

Fig. 3. X-band niobium test deflector (8.7 GHz, π mode).

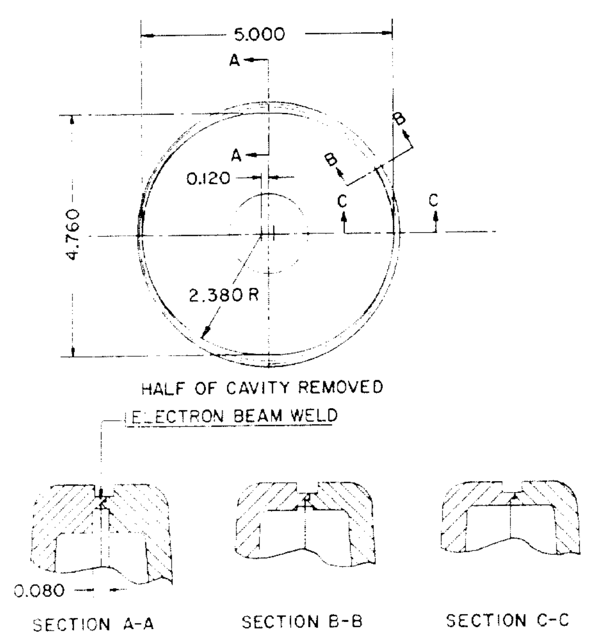

Fig. 4. Deflector geometry with mode stabilizer.

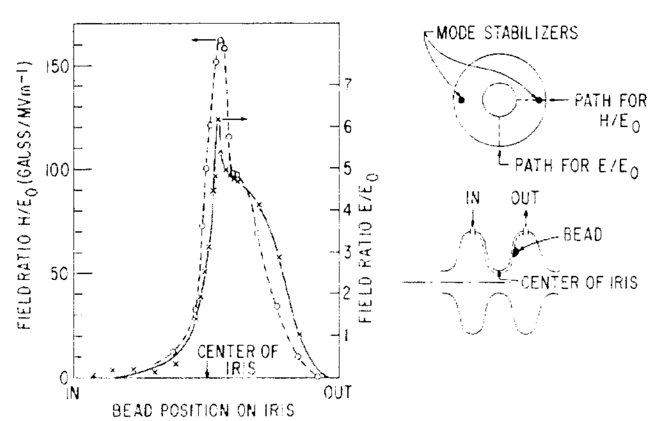

Fig. 5. H/E_0 and E/E_0 on surface of iris.