DESIGN AND MEASUREMENTS OF A DEFLECTING MODE CAVITY FOR AN RF SEPARATOR

L. Bellantoni, H.T. Edwards, M. McAshan, FNAL, Batavia, IL 60510, USA
R. Wanzenberg, DESY, Hamburg, Germany

Abstract

The Fermilab Main Injector can produce intense 120 GeV/c proton beams for fixed target experimentation. Two deflecting mode RF systems can be used to separate charged kaons from a momentum selected secondary beam, consisting of pions, kaons and protons, using a time of flight method. We present the RF design of a 3.9 GHz superconducting cavity which operates in the deflecting (TM110) pi-mode and the dependence of the RF parameters on the cavity shape, as determined with finite difference calculations. End cell compensation has been treated, providing cell-to-cell field flatness. First results from measurements on a prototype cavity are shown. We demonstrated that it is possible to tune the deflecting mode of a five cell cavity with bead pull measurements. Effects relating to the polarization of the modes are discussed.

1 INTRODUCTION

The Fermilab Main Injector will produce intense beams of protons of a momentum of 120 GeV/c for fixed target experiments. It has been proposed [1] to use the generated secondary particles, a mix of protons, pions and kaons, to perform studies of CP violation using kaon decays. After a momentum selection stage, the protons, pions and kaons have the same momentum but different velocities due to their different masses. The kaons will be separated by a time of flight separation using two rf-systems. The set-up is schematically shown in Fig. 1. Kaons, pions and protons are kicked by an transverse mode rf-system (#1) and transfered through an optical system, which performs a $-I$ mapping for the second rf-system. The pions arrive earlier at the second rf-station and are kicked onto a beam stopper while the kaons arrive later and pass the beam stopper. The protons arrive later than the pions and kaons and are kicked to the beam stopper, too. For the required phase slip of $2\,\pi$

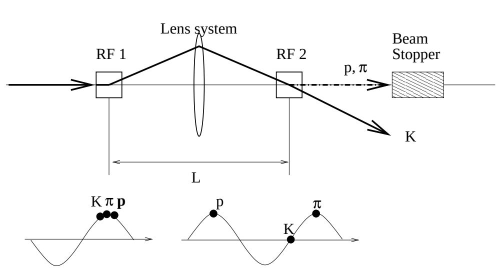

Figure 1: Kaon beam separation

between the pions and protons, the slip between the pions and kaons is $\sim\pi/2$. This leads to the condition

$$f \cdot L \approx \frac{\Delta\phi_p}{2\,\pi}\,2\,c\,\gamma_p^2 \approx 330\ \mathrm{GHz}\cdot\mathrm{m}.$$

For $22\,\mathrm{GeV/c}$ kaons the distance L should be reasonably short, consistent with a fraction of the total beam line length and acceptable frequencies. The following choice fulfill the requirements:

$$f = 3.9\ \mathrm{GHz}, \quad L \approx 86.4\ \mathrm{m}.$$

The main design parameter of the separator system are summarized in table 1. A superconducting rf-system is required due to the long extracted beam duration of 1 second per cycle. The first generation of particle separators was constructed at Brookhaven and at CERN using traveling-wave copper structures. The first superconducting rf-separator (KfK Karlsruhe - CERN design) began operation in 1977 [2] at deflecting gradients of upto 1.4 MV/m. Using the recently achieved advance in superconducting rf-technology of the TESLA collaboration [3], the Fermilab rf-deflector design gradient is 5 MV/m. This has already been exceeded in single cell measurements (see below).

Table 1: Separator System Parameters

Beam momentum, pc	22	GeV
Main Injector cycle time	3	sec
Extracted beam duration	1	sec
Main Injector intensity used	5×10^{12}	proton
Secondary beam intensity	$\approx 1.4\times10^{10}$	
Secondary beam current	$\approx 2.2\times10^{-9}$	amp
RF Station Configuration	2	stations
Distance between stations	86.5	m
Station deflection angle	0.68	mrad
Deflection gradient	5	MV/m
Station effective RF length	3	m
Total # cavities	12	
Total cryo power @2.0K	120	W
Q_{ext}	6×10^7	
RF power @ 5MV/m	300	W/m

2 RF DESIGN OF A DEFLECTING MODE CAVITY

A 13-cell 3.9 GHz cavity operating in the π-mode has been chosen as the baseline design for the rf-separator. The shape of a cavity half cell is described with two circle segments which are smoothly connected by a straight line. An overview on all considered cavity shapes can be found in

Fig. 2. The shape A15 was used for the copper and niobium model cavity prototypes, which have been built for first measurements, while the shape C15 is the selected design. The cavity parameters are summarized in table 2.

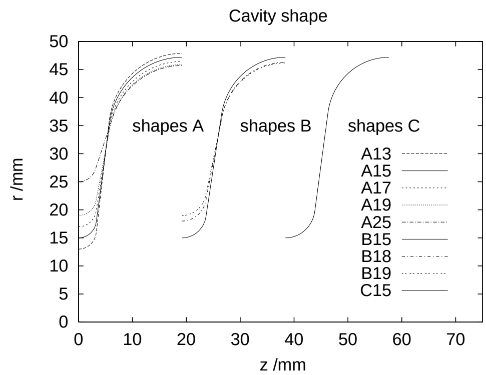

Figure 2: Half cell shapes of examined cavity designs

Table 2: Separator RF Cavity Parameters for C15 design

Frequency	3.9	GHz
mode	π, $\approx$TM110	
Equator diameter body, (end)	94.36 (95.10)	mm
Iris diameter	30	mm
Cell length	38.4	mm
cells/cavity	13	
Effective RF length/cavity	499.2	mm
$(R/Q)'$/cavity	351	Ohm
$(P = V^2/2(R/Q)' \times Q)$		
V_{trans}	5	MV/m
E_{peak}@ 5 MV/m	18.5	MV/m
B_{peak}@ 5 MV/m	0.077	T
Coupling factor $(f_0 - f_\pi)/f$	0.043	
$f_\pi - f_{\pi-1}$	1.0	MHz
polariz-tune-split.	10 . . . 40	MHz
tuning range	$\pm$ 1	MHz
G_1 =Q$\times$ R_{sur}	228	Ohm
R_{sur} @ 2K, T_c/T=4.6	1.1×10^{-7}	Ohm
Q@R_{sur}	2.1×10^9	
Power dissipated@5MV, 2K	8.5	W/m
Q_{ext}	6×10^7	
full bandwidth f/Q_{ext}	65	Hz
U (stored energy)	0.73	Joules/m

The computer code MAFIA [4, 5] has been used to investigate the basic design parameters. The most important design parameters are $(R/Q)'$ and the peak magnetic field near the surface B_{max}, which limits the maximum field in a superconducting cavity.

The dispersion curve of the lowest deflecting mode passband is shown in Fig. 3 for the cavity shapes A13, A15, A17, A19 and A25. The slope of the dispersion curves is changing from negative values (backward wave structure, or negative group velocity) for the shapes A13 and A15 to positive values (forward wave structure, or positive group velocity) for the shapes A17, A19 and A25. A 13-cell cavity will be harder to tune if the dispersion curve is very flat since more than one mode may be excited during the tuning procedure which is performed at room temperature. Therefore a further design criteria is the total width of passband and the frequency difference between the π-mode and the mode next to the π-mode, often called the $\pi - 1$ mode. A frequency difference between the $\pi - 1$ and π-mode of $\delta f/f_\pi = 3 \cdot 10^{-4}$ should be sufficient to tune a 13-cell cavity.

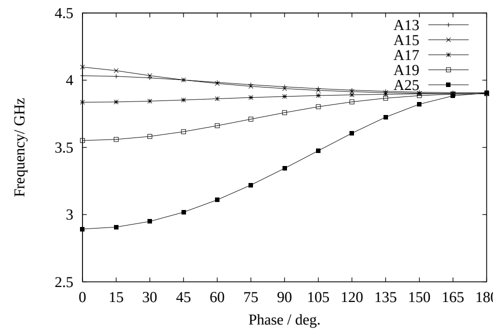

Figure 3: Dispersion curve of the first dipole passband of the cavities of shape A13 . . . A25

The results of MAFIA calculations of these important parameters for one cell cavities are given in table 3. Furthermore the geometry parameter (G_1) has been calculated. G_1 is about $250\,\Omega$ for the cavities of shape A and about $230\,\Omega$ for shape B and C, almost independent from the iris radius. The quantity $(R/Q)'$ depends linearly on the iris radius. An end-cell design has been found which guarantees a good field flatness in a 13-cell cavity and simultaneously enables a good coupling from a coaxial coupler to deflecting mode. Fig. 4 shows the electric field of the deflecting π-mode in one half of a 13-cell with this special end-cell design. Further details of the multi-cell design study and additional investigations using a two chain equivalent model can be found in [6].

Table 3: Summary of the results obtained from the MAFIA calculations for one-cell cavities.(B_{max} at 5 MV/m)

Label	f/MHz	$(R/Q)'$ /Ω	B_{max}/T	$\delta f/f_\pi$ / 10^{-4}
A13	3905.9	31.1	0.077	-3.15
A15	3898.7	27.6	0.087	-2.36
A17	3900.6	23.1	0.097	1.53
A19	3900.1	18.6	0.107	9.4
A25	3905.6	8.1	0.135	55.7
B15	3904.7	27.3	0.077	-2.81
B18	3900.7	20.8	0.091	2.72
B19	3892.3	18.6	0.095	6.26
C15	3899.7	27.3	0.073	-3.04

3 MEASUREMENTS

A five cell A15 prototype, originally constructed of reactor grade niobium as a study in fabrication technology, has been polarized and tuned for field flatness. The cavity, shown in Fig. 5, was polarized by compressing it transversely to introduce two small flats in cell after the cavity

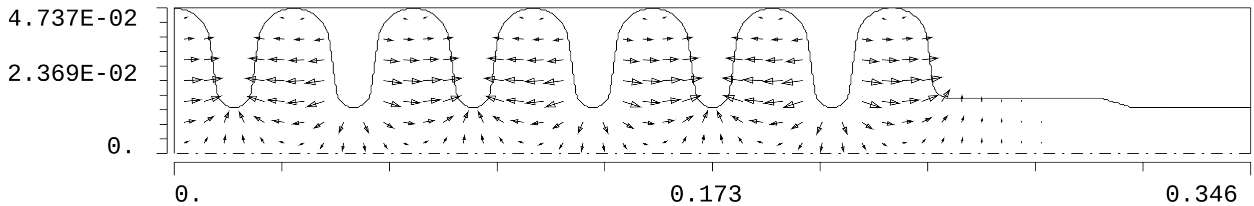

Figure 4: 13-cell cavity of shape C15, electric field of the π-mode ($f = 3.8996$ GHz).

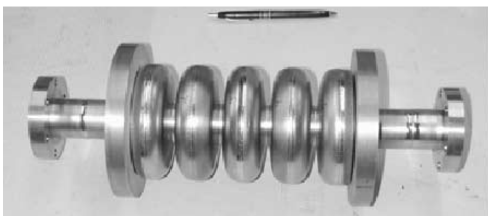

Figure 5: Five cell Niobium prototype transverse mode cavity.

was manufactured. The transverse diameter at the flats was 3.17mm less than the equatorial diameter of cells and this introduced an 8.025MHz splitting in the frequencies of the two polarizations. The cavity did not have compensated end cells, and the field energy in the end cells was correspondingly less than for the three central cells.

This cavity was tuned by pulling a round metallic bead down the axis of the cavity; the frequency is perturbed upwards by the deflecting magnetic field when the bead is in the center of a cell, and downwards in the iris from the electric fields shown in Fig. 4 (which also contributes to the deflection). We used the maximal upward frequency perturbation of each cell as a measure of the oscillation amplitude squared for an LC tank in an equivalent lumped element circuit. Although a circuit with two chains of LC tanks [7] is needed to accurately model the frequencies of the TM and TE passbands, a simple model with one chain of tanks is sufficient to achieve field flatness if the intercell coupling is calculated using the measured spacing between the π and the $4\pi/5$ mode. Fig. 6 shows the bead pull result after tuning, and the simulated bead pull result from MAFIA.

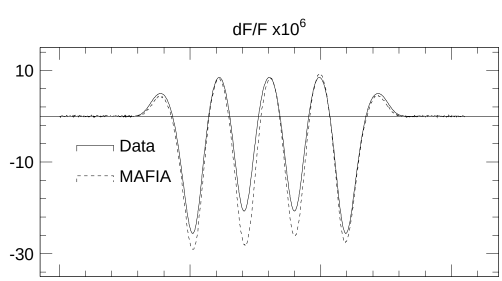

Figure 6: Results from bead pull measurements

A single cell cavity of high quality niobium in the C15 design has been cold tested and has achieved [8] surface field levels in excess of the required 77 mT.

4 CONCLUSION

The passband structure of deflecting mode cavities with π-mode cell length, which mainly differ by the cell-to-cell coupling, has been investigated. In the strongly-coupled regime, the deflection band is of the forward-wave type with the π-mode at the high-frequency end of the band, and in the weakly-coupled regime the deflection band has a backward wave and the π-mode is the lowest frequency in the band. The deflecting modes are of hybrid (TM and TE) character like any dipole mode in an accelerating structure. At least in the weakly coupled case the TM-like modes of the deflecting band lie lower in frequency than the TE-like modes, which form the second passband.

The weakly coupled cavity shape C15 has been selected as the shape to use in the R&D program. Strongly coupled shapes with large irises seem inappropriate because of the complexity of their mode patterns, their lower $(R/Q)'$, and higher peak magnetic field, despite the advantage of greater bandwidth.

5 REFERENCES

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