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BEAM DYNAMICS STUDIES OF 499 MHz SUPERCONDUCTING RF-DIPOLE DEFLECTING CAVITY SYSTEM*

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Abstract

A 499 MHz deflecting cavity has been designed as a three-way beam spreader to separate an electron beam into 3 beams. The rf tests carried out on the superconducting rf-dipole cavity have demonstrated that a transverse voltage of 4.2 MV can be achieved with a single cavity. This paper discusses the beam dynamics on a deflecting structure operating in continuous-wave mode with a relativistic beam. The study includes the analysis on emittance growth, energy spread, and change in bunch size including effects due to field non-uniformities.

INTRODUCTION

A deflecting cavity system separates a single beam into multiple beams by applying a transverse momentum to the center of each bunch that displaces the bunch off axis at an angle. The Panofsky-Wenzel Theorem [1] describes the concept of producing a transverse momentum using the electromagnetic fields in an rf structure. A single beam can be separated into multiple beams depending on the rf phase at which the transverse kick is applied.

Jefferson Lab currently uses a three-way beam spreader system that separates the oncoming electron beam with a repetition rate of 1497 MHz in to 3 beams, that are delivered to the 3 experimental halls (Hall A, B and C) [2]. The rf separators system operating at 499 MHz will apply the transverse kick as shown in Fig. 1, that enables the delivery of the highest energy beam simultaneously to hall the 3 experimental halls.

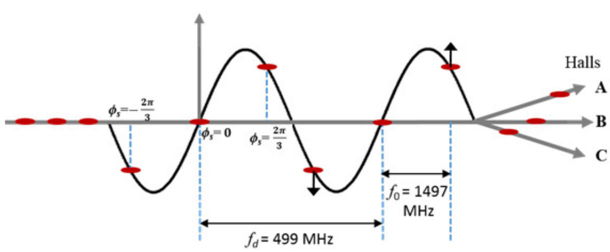

Figure 1: Bunch separation in the Jefferson Lab three-way beam spreader.

The rf separation for the 6 GeV CEBAF machined was achieved with the set of normal conducting cavities. The 4-rod cavity operating in TEM mode are also being used in the 12 GeV machine [2]. The optics in the beam switch yard region had been reworked that relaxed the transverse kick requirement for the 12 GeV upgrade [3]. The rf separators are required to deliver a transverse kick of 3.3 MV in order to deliver the required separation of 297 μrad in vertical direction. The required separation gives a ±17 mm separation at the extraction magnets [4].

RF-DIPOLE CAVITY

A superconducting rf deflecting cavity was initially proposed for the Jefferson Lab 12 GeV upgrade. The optimized 499 MHz rf-dipole cavity design shown in Fig. 2 was successfully fabricated and rf tested [5, 6, 7]. The rf properties of the cavity are listed in Table 1.

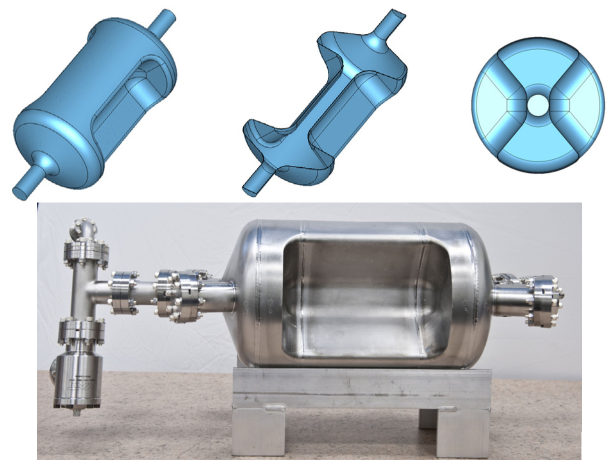

Figure 2: 499 MHz rf-dipole cavity design (top-left) with cross sections along z axis (top-center) and y axis (top-right), and the fabricated cavity (bottom).

Table 1: RF Properties of the 499 MHz rf-Dipole Cavity

Parameter	Value	Units
$\lambda/2$ of π mode	300.4	mm
Cavity length	440.0	mm
Cavity diameter	242.2	mm
Aperture diameter (d)	40.0	mm
Deflecting voltage (V_T*)	0.3	MV
Peak electric field (E_P*)	2.86	MV/m
Peak magnetic field (B_P*)	4.38	mT
B_P* / E_P*	1.53	mT/(MV/m)
Energy content (U*)	0.029	J
Geometrical factor	105.9	Ω
$[R/Q]_T$	982.5	Ω
$R_T R_S$	1.0×10^5	Ω^2
Operating Parameters		
Deflecting voltage (V_T)	3.3	MV
Peak electric field (E_P)	32	MV/m
Peak magnetic field (B_P)	49	mT
Power dissipation (P_{diss})	1.31	W

At E_T* = 1 MV/m

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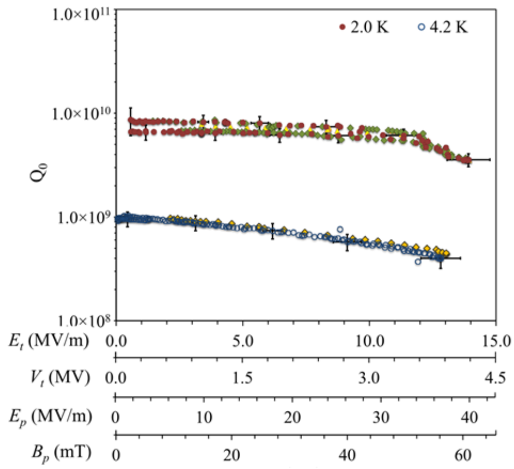

Figure 3: Quality factor at 4.2 K and 2.0 K of the 499 MHz rf-dipole cavity.

Figure 3 shows the measured intrinsic quality factors (Q_0) for the rf tests carried out at both cryogenic temperatures of 4.2 K and 2.0 K. The requirement of 3.3 MV transverse kick is easily achieved at both temperatures by a single rf-dipole cavity. At the required transverse kick the deflecting cavity will operate with moderate peak fields of 32 MV/m and 49 mT. The required kick of 3.3 MV can be achieved by a single rf-dipole cavity.

DEFLECTING CAVITY SYSTEM

The transverse kick (V_T) required by the deflecting cavity is determined by

$$V_T = E_0 \text{ [eV] } \theta \text{ [rad]} \qquad (1)$$

where E_0 is the beam energy and θ is deflecting angle. The transverse kick relates to the transverse momentum exerted by the electromagnetic fields in cavity as following,

$$\vec{p}_T = \int_{-\infty}^{\infty} \vec{F}_T dt = \frac{q}{v}\int_{-\infty}^{\infty}\left[\vec{E}_T + \left(\vec{v}\times\vec{B}_T\right)\right]dz \qquad (2)$$

where F is the Lorentz force experienced by a particle with a velocity of $\vec{v}$ traversing through the cavity with electric field of E_T and magnetic field of B_T.

For a cavity of length L with a transverse kick in horizontal direction the transverse momentum relation to the transverse voltage can be expressed as

$$p_x = \frac{eV_T}{c}\sin\left(\frac{\omega z}{c} + \phi_s\right) \qquad (3)$$

where ω is the cavity frequency, c is speed of light and ϕ_s is the synchronous phase [8, 9].

A particle on crest receives the maximum transverse kick and by varying the phase, at which the transverse kick is applied the beam can be separated into multiple beams. A crabbing cavity will operate at a zero phase that gives a kick to head and tail of the bunch in opposite direction.

The CEBAF rf separator will apply the transverse kick at the phases of +120^0 for Hal A, -120^0 for Hall C and the undeflected beam at 0^0 for Hall B as shown in Fig. 1.

BEAM DYNAMICS STUDIES

The transverse momentum applied at each bunch has an effect on other beam properties such as emittance and energy spread. The emittance change for a beam passing through a deflecting cavity for a cylindrical shaped bunch is given by [8]

$$\varepsilon_{n,rms} = \frac{eV_T}{4\sqrt{3}mc^2}\frac{\omega}{c}\sigma_y I_b \qquad (4)$$

where σ_y is the transverse beam size and I_b is beam current.

The Using ASTRA [10], two electron beams were tracked through the cavity. Both were truncated Gaussian distributions of 3σ in all dimensions. One case assumed emittance values similar to what is currently produced at CEBAF, while the other is what the specifications of CEBAF require [11]. The initial beam properties are shown in Table 2, while the resulting beams are shown in Table 3.

Table 2: CEBAF Beam Properties for (1) Current Operation and (2) required by Specifications

Parameter	(1)	(2)	Units
Beam Energy	11.023		GeV
Normalized $\varepsilon_{x,rms}$	3.688	21.57	mm-mrad
Normalized $\varepsilon_{y,rms}$	11.47	150.9	mm-mrad
σ_x	0.1085	0.2623	mm
σ_y	0.1555	0.5642	mm

Table 3: Beam Properties of the $(1)_{A,C}$ Deflected and $(1)_B$ Undeflected Beam for (A) Current Operational Parameters and (B) Required Specifications

σ_z (mm)	$\Delta\varepsilon_x$ (μm-mrad)			
	(A)		(B)	
	$(1)_{A,C}$	$(1)_B$	$(2)_{A,C}$	$(2)_B$
100	15.6	107.3	-12	143
90	11.7	88.6	-16	122
80	8.2	71.7	-18	103
70	5.3	56.6	-21	86
60	2.7	43.3	-22	71
50	7.0	31.8	-24	58
40	-0.9	22.1	-24	47
30	-2.0	14.4	-25	37
20	-2.6	8.5	-25	29
10	-2.8	4.4	-24	24
$\Delta\sigma_x$ (µm)	-1.8	-1.7	-4.1	-4.0
$\Delta\sigma_y$ (µm)	2.2	2.2	7.9	8.0

Both beams were tracked assuming passage to all three halls, though the deflecting beams were nearly identical regardless of the direction of deflection. Only the vertical emittance changes as the beam traverses the cavity.

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Overall, it is clear that the emittance growth experienced by the beam increases as σ_z is increased. Additionally, the growth is larger for the undeflected beam than the deflected ones. Deflection and displacement of the tracked beam to all three halls is shown in Fig. 4. Of note is the net displacement of the undeflected beam. This displacement is approximately 42 μm, which is consistent with previous results [8]. Changes in the size (σ_x and σ_y) are constant for a given case (initial beam and deflected beam).

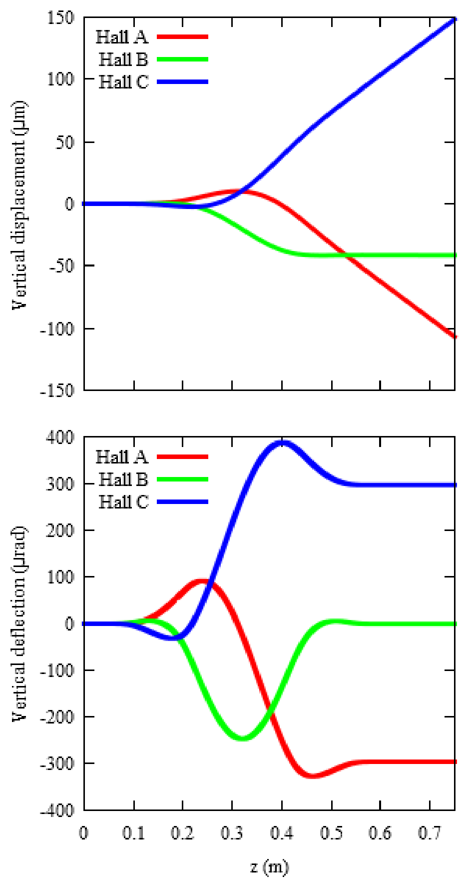

Figure 4: Displacement (top) and deflection (bottom) of three beams.

Deflecting rf cavities provide a longitudinal voltage proportional to the transverse offset. The corresponding change in longitudinal voltage (V_z) can be determined by

$$V_z = \frac{\omega}{c} x_0 V_T . \tag{5}$$

This corresponding energy spread (ΔE) then can be determined by

$$\Delta E = e\frac{\omega}{c} y_0 V_z \cos\left(\frac{\omega z}{c} + \phi_s\right) \tag{6}$$

related to the offset (y_0). There is no change in the energy spread of the beam.

FIELD NON-UNIFORMITY AND MULTIPOLE COMPONENTS

The normalized off-axis field variation is shown in field non-uniformity is shown in Fig. 5. For small bunches such as in CEBAF the off-axis variation in V_T is negligible. However the corresponding higher order multipole components may lead to emittance growth.

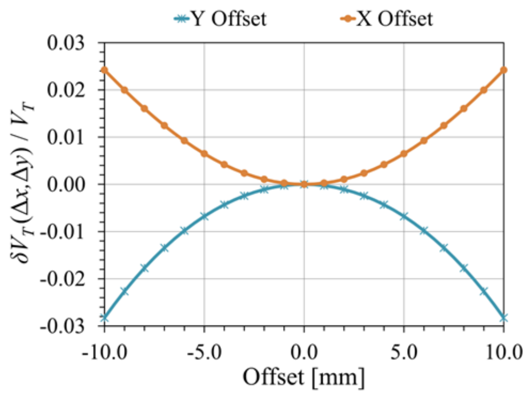

Figure 5: Quality factor at 4.2 K and 2.0 K of the 499 MHz rf-dipole cavity.

Higher order multipole components are calculated using

$$b_n = j\frac{n}{\omega}\frac{1}{r^n}\int_{-\infty}^{\infty}\left[\int_0^{2\pi} E_z(r,\phi,z)\cos(n\phi)\,\mathrm{d}\phi\right]e^{j\omega t}\mathrm{d}z \tag{7}$$

by Fourier series expansion of the field data [12]. The rf-dipole cavity has non zero normal components (b_n) where skew components (a_n) are zero. The (b_n) up to order n=5 are shown in Table 4. The values at V_T = 3.3 MV are compared with the corresponding values obtained for the magnets at beam switchyard area (BSY) [13]. The higher order multipole components are several orders of magnitude low compared to that from the magnets.

Table 4: Higher Order Multipole Components

Parameter	From RF Cavity	From Magnets	Units
b_2	0.0017	18.4	mT/m
b_3	2871	5.0×10^5	mT/m^2
b_4	14.9	4.0×10^6	mT/m^3
b_5	2.0×10^6	7.3×10^8	mT/m^4

CONCLUSION

A superconducting rf-dipole cavity at 499 MHz has been fabricated and rf tested. The performance achieved at 2.0 K allows the use of a single cavity for the required deflection of 3.3 MV. The beam dynamics study shows that the emittance growth increases with the bunch length, but is acceptable for both operational and specified beam parameters. The calculated higher order multipole components are very low compared to that from the magnets at the BSY.

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