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BEAM DYNAMICS STUDIES OF PARALLEL-BAR DEFLECTING CAVITIES*

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Abstract

We have performed three-dimensional simulations of beam dynamics for parallel-bar transverse electromagnetic mode (TEM) type RF separators: normal- and superconducting. The compact size of these cavities as compared to conventional TM_{110} type structures is more attractive particularly at low frequency. Highly concentrated electromagnetic fields between the parallel bars provide strong electrical stability to the beam for any mechanical disturbance. An array of eight 2-cell normal conducting cavities or a one- or two-cell superconducting structure are enough to produce the required vertical displacement at the Lambertson magnet. Both the normal and superconducting structures show very small emittance dilution due to the vertical kick of the beam.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson lab is in the stage of an energy upgrade from 6 GeV to 12 GeV; the schematic is shown in Fig. 1. The 12 GeV option requires 10 additional cryomodules and an arc to direct the highest energy (12 GeV) $5\frac{1}{2}$ pass beam to hall-D. Beam extraction in the existing setup is done with the help of a system consisting of seven warm RF separator cavities and a series array of three on the 5th pass is capable of sending highest energy (6 GeV) beams to the three different experimental halls simultaneously. The 1497 MHz continuous electron beam is composed of three interlaced variable intensity 499 MHz beams that can be independently directed from any of the five passes to any of the three experimental halls (A, B and C). However, the existing setup of the deflectors will not be adequate enough to serve the purpose in the case of the proposed 12 GeV upgrade of the machine. To restore the capability, several options including the extension of existing CEBAF normal conducting (NC) structures or a new TEM-type superconducting (SC) design are under investigation. The electromagnetic characterizations of the TEM-type super-conducting structure have been confirmed by the three-dimensional simulations [1]. Also, the rigorous analysis of the existing CEBAF normal conducting cavity from the RF design view point has been reported in [2]-[3] and more importantly the device is working. To achieve the required deflection in the 12 GeV machine, a combination of eight normal conducting cavities is proposed. In this paper, we report the beam dynamics studies of the superconducting and the normal conducting structures as shown in Figs. 2 and 3 respectively. The basic properties of these cavities are summarizes in Table 1.

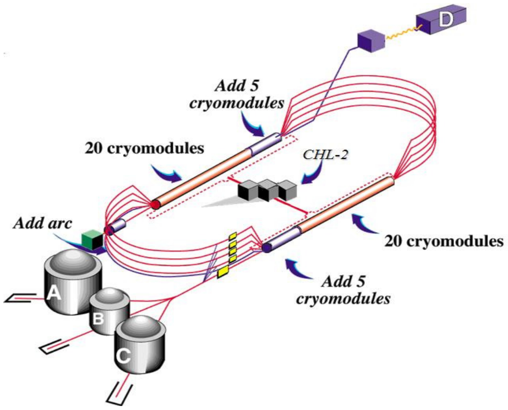

Figure 1: CEBAF 12 GeV upgrade schematic.

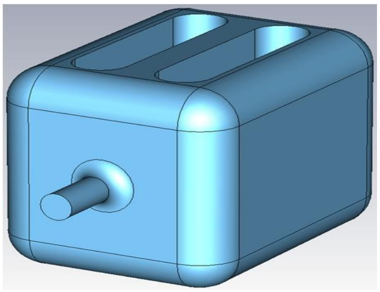

Figure 2: TEM-type SC cavity as illustrated in [1].

SIMULATIONS PROCEDURE

The numerical simulations of beam dynamics studies have been carried out by three different packages: general particle tracer (GPT) [4], g4beamline [5] and CST particle tracking simulator [6]. The GPT and g4beamline simulation software packages use fieldmaps for tracking particles, which is obtained from the eigen mode solver of the

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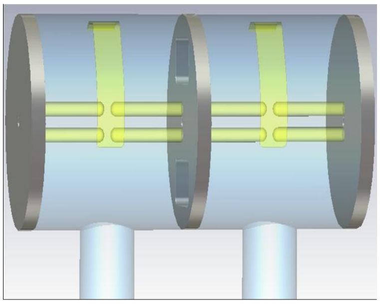

Figure 3: Existing CEBAF NC cavity as discussed in [3].

Table 1: Properties of TEM-type SC and CEBAF NC Structures as shown in Figs. 2 and 3

Parameters	**TEM-type SC**	**CEBAF NC**
Freq. of π-mode (MHz)	499.2	499
$\lambda/2$ of π-mode (mm)	300.4	300.4
freq. of 0-mode (MHz)	517.8	537
Cavity length (mm)	394.4	300
Cavity width (mm)	290	292
Bars height (mm)	304.8	20
Bars width (mm)	67	20
Bars length (mm)	284	135
Aperture diameter (mm)	40	15
Deflect. voltage (V_T^*) (MV)	0.3	0.3
Peak E-field (E_P^*) (MV/m)	1.85	3.39
Peak B-field (B_P^*) (mT)	6.69	8.87
Energy content (U^*) (mJ)	31	1.2
Geometric factor (Ω)	67.96	34.9
$(R/Q)_T$ (Ω) at E_T^* = 1 MV/m	933.98	24921

CST Microwave Studio. GPT is a well established three-dimensional time domain computer program for studying the particle dynamics in EM fields. The tracking algorithm is based on the fifth order Runge-Kutta method with adaptive step size and takes into account the space charge physics and other nonlinearities. However, g4beamline is a reliable and robust computer program based on GEANT4 [7]. GEANT4 is a single particle tracking program in space while g4beamline incorporates collective tracking in time and includes space charge physics. Moreover, it provides visualization of the simulated objects. On the other hand, the particle tracking simulator of CST Microwave Studio is a new development, and provides much flexibility for studying beam dynamics of complex objects.

To determine the operating phase numerically, we compute the deflection at the exit of the cavity for one complete RF cycle ϕ_{rf} = 0° to 360° as shown in Fig. 4. As the cavity is half-wave long, we expect the deflection to follow a cosine function. The first zero crossing at ϕ_{rf} = 90° corresponds to zero deflection and is defined as the reference phase ϕ_{ref}. As the hall-B beam is undeflected (directed straight), the reference phase is representative of the beam going to hall B i.e. $\phi_B = \phi_{ref}$. Therefore, the corresponding phases of the beam directed to hall A and C (see Fig. 1) are given by $\phi_{A,C} = \phi_B \pm 120°$. This phase convention will be used throughout this study unless stated explicitly.

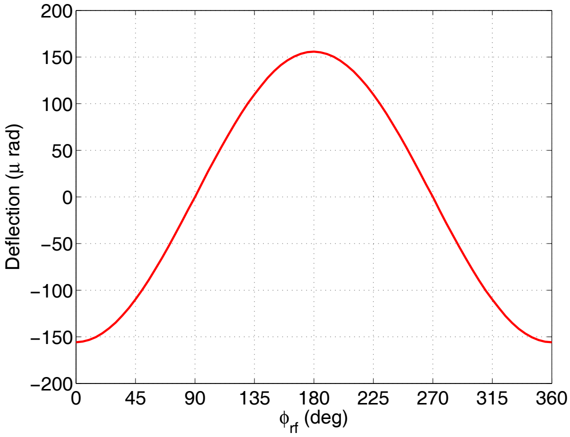

Figure 4: Vertical deflection versus RF phase at the exit of the cavity shown in Fig. 2.

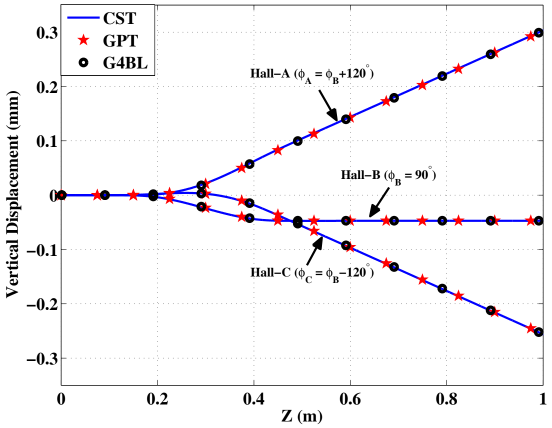

Figure 5: Vertical displacement of an 11 GeV electron for RF phases ϕ_A, ϕ_B and ϕ_C of the superconducting cavity (see Fig. 2). Simulation results are compared using the CST particle tracker, GPT and G4BL (g4beamline) computer codes.

In the 12 GeV upgrade, beam in each pass will get an acceleration of 2.2 GeV resulting in 11 GeV for the 5th pass extraction. To avoid nonlinear effects and gain insight of the cavity performance, we track an 11 GeV electron in the presence of full 3D RF fields near the axis of the superconducting structure. A comparison of results obtained from CST particle tracker, GPT, and g4beamline computer programs are illustrated in Fig. 5. We observe three different tracks which are vertical displacements corresponding to the three different RF phases ϕ_A, ϕ_B and ϕ_C respectively. Also notice the nonzero residual orbit offset corresponding to the reference phase. This is mainly due to the finite transit time from a thick lens in contrast to the thin lens approximation.

The requirement from the optics design stand point is to achieve a vertical displacement of 17 mm for hall A and C at a distance of 43 m where the Lambertson magnet is located. To achieve this goal, we are assessing the superconducting structures and an array of normal conducting structures. Figs. 6 and 7 show the required displacement obtained from a single superconducting structure and an array of eight 2-cell normal conducting cavities.

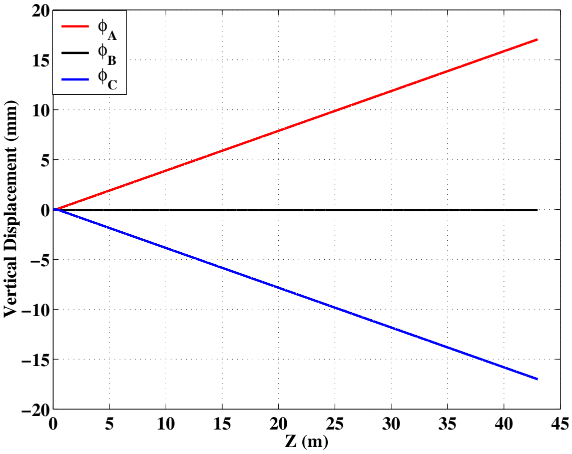

Figure 6: Vertical displacement at the Lambertson magnet corresponding to RF phases ϕ_A, ϕ_B and ϕ_C and deflecting voltage V_{def} = 5.06 MV obtained from a single cell superconducting structure.

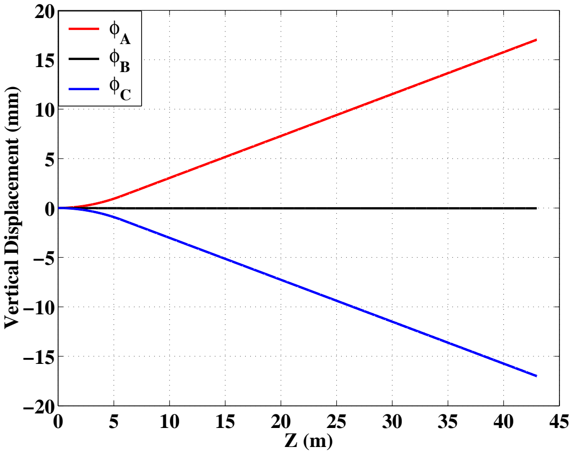

Figure 7: Vertical displacement at the Lambertson magnet corresponding to RF phases ϕ_A, ϕ_B and ϕ_C and deflecting voltage V_{def} = 5.06 MV obtained from 8 2-cell normal conducting cavities.

Noteworthy points are as follows. First, we observe three distinct tracks, and all the nonlinearities observed in the vicinity of the structure (see Fig. 5) disappear. The upward and downward diverging tracks correspond to the RF phases ϕ_A and ϕ_C and the central track is representative of the reference ϕ_B. Second, for the normal conducting cavity arrangement we observe the vertical displacement of ∼ 1.3 mm at the final exit. This violates the beam stay clear condition of 6.5 mm from either wall, which can be resolved by using 6-cells where the vertical displacement at the final exit is about 0.9 mm. Third, emittance blow-up is small for the parameters of interest, and it follows the linear relationship with bunch length (see Fig. 8) for beam sizes smaller than the RF wavelength.

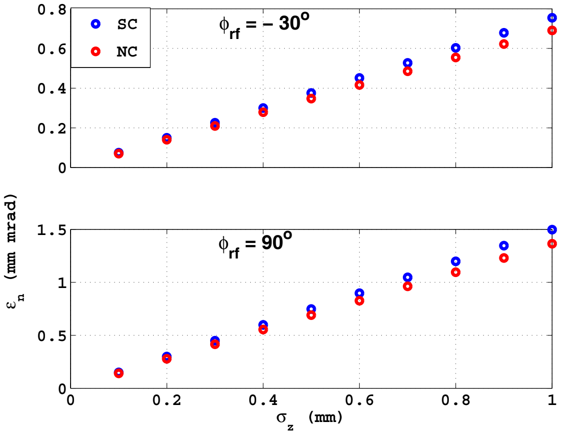

Figure 8: Comparison of normalized rms transverse emittance ($\epsilon_{n,x}$) between normal and superconducting cavities for different bunch lengths (σ_z). The distribution is uniform with zero initial emittance corresponding to RF phases $\phi_{A,B,C}$.

CONCLUSION

In this paper, we report the beam dynamics studies of 11 GeV RF separators for 12 GeV upgrade of CEBAF. This study confirms that an array of eight normal conducting cavities and the superconducting structure have the same beam properties and hence either one can be used as a final deflector. There is a small dilution of beam emittance due to vertical kick.

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