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NUMERICAL STUDIES OF NORMAL CONDUCTING DEFLECTING CAVITY DESIGNS FOR THE ELBE ACCELERATOR

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Abstract

Currently, in the electron linac ELBE there is a single beam line. Therefore, at any given time only single user can use the beam. Moreover, as different user experiments require distinct beam intensity settings, not all the experiments fully utilize the 13 MHz CW beam capability of the facility. To utilize the full beam capacity, multiple beam lines can be established by using an array of transverse deflecting structures. For that, an RF cavity was the design choice due to its inherent advantages with respect to repeatability of the kick voltage amplitude and phase, and the possibility of CW operation in the MHz range. Potential design candidates are the CEBAF RF separator, the three proposed crab cavities for the HL-LHC upgrade project, and a novel NC deflecting cavity design. In this comparative study, the figures of merit of the cavities are computed from electromagnetic field simulations for a transverse voltage of 300 kV. This comparative study supported our selection of the deflecting cavity design for ELBE.

INTRODUCTION

Radio-frequency deflecting (RFD) cavity design has evolved significantly since its first use in 1960 for particle separation and has found many applications like beam diagnostics [1], crabbing of the beams in KEKB [2] and LHC [3], etc. Additionally, these deflecting structures are deployed as beam separators in CEBAF [4], and these structures deliver an opposite transverse kick to the alternating bunches thereby splitting a single beam with bunch repetition rate (BRR) of 'f_{brr}' into two beams with a BRR of '$f_{brr}/2$' as shown in Fig. 1. By using an array of deflecting structures, it is intended to increase the number of beamlines in ELBE which will facilitate in utilizing the full beam capacity of the facility.

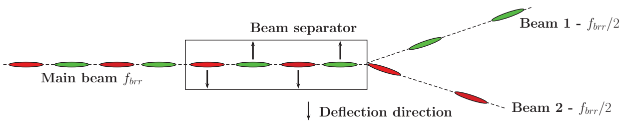

Figure 1: Sketch representing the working principle of a beam separator.

A detailed study of the different deflecting structures suggested that an RFD cavity is a suitable choice as a beam separator for ELBE and this is due to its inherent advantages with respect to repeatability of the kick voltage amplitude and phase, and the possibility of CW operation in the MHz range. The main beam parameters and cavity requirements for the prototype beam separator are given in table 1. Five promising RFD cavity designs are considered in this study and numerical simulations are performed to obtain the figures of merit (FOM). In particular, the surface power loss density and the total RF loss of a cavity are emphasized, as these parameters decide on the cooling and RF power requirement for a normal conducting cavity [5]. Furthermore, variation of the transverse kick around the axis of a cavity is also presented.

Table 1: Beam Parameters and Cavity Requirements considered for the Prototype Beam Separator

Parameter	Symbol	Value	Unit
Beam energy	E_{beam}	100	MeV
Bunch repetition rate	f_{brr}	1	MHz
Deflection angle	θ	3	mrad
Kick homogeneity (GFR)[@]	$\delta V_\perp / V_\perp$	0.15	%
RF frequency	f_{rf}	260.5	MHz
Beam pipe radius	r_{bp}	20	mm
Cavity aperture	d_{ape}	40	mm

[@] Circular area of 5 mm centered on the beam axis

CALCULATION OF FOM

A charged particle traversing along the axis of an RFD cavity gains a transverse momentum $\Delta p_\perp$ and gets deflected by an angle θ which is given as

$$\theta = \frac{\Delta p_\perp}{p} \approx \frac{\Delta p_\perp}{p_\parallel} = \frac{eV_\perp}{E_{beam}}, \tag{1}$$

where p and $p_\parallel$ are the total momentum and longitudinal momentum of the charged particle at the exit of the cavity, $V_\perp$ is the integrated transverse voltage delivered by the cavity, and E_{beam} is the beam energy. Therefore, to deflect an electron beam of 100 MeV by an angle of 3 mrad the cavity should deliver a $V_\perp$ of 300 kV. The on-axis transverse electric ($\vec{E}_\perp$) and magnetic field ($\vec{B}_\perp$) components contribute to the integrated transverse voltage and is given by

$$V_\perp = \frac{\Delta \vec{p}_\perp c}{e} = \int_{-\infty}^{\infty} \left(\vec{E}_\perp + \vec{v} \times \vec{B}_\perp \right) e^{ikz} dz, \tag{2}$$

where $k = 2\pi f_{rf}/c$, f_{rf} is the frequency of the deflecting mode, c is the velocity of the light and $\vec{v}$ is the velocity of the

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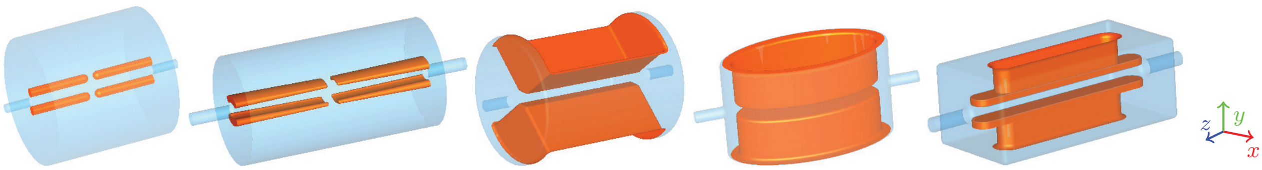

Design-I Design-II Design-III Design-IV Design-V

Figure 2: Geometry of the five probable deflecting cavity designs: CEBAF deflector (Design-I), probable crab cavities of LHC (Design-II,III,IV) and a novel NC deflecting cavity (Design- V). The outer surfaces of the cavity are made transparent to highlight the inner parts. The beam traverses along the z-axis.

particle. An alternative method would be to use the Panofsky-Wenzel theorem to calculate $V_\perp$. Further, the transverse shunt impedance ($R_\perp/Q$) and the total RF power loss (P_{loss}) in a cavity are defined as

$$\frac{R_\perp}{Q} = \frac{V_\perp^2}{\omega U} \quad \text{and} \quad P_{loss} = \frac{V_\perp^2}{(R_\perp/Q)Q}, \qquad (3)$$

where U is the stored energy in a cavity and Q is the intrinsic quality factor.

SIMULATION RESULTS

The five cavity designs considered as a potential RFD cavity for ELBE are shown in Fig. 2. Design-I represents the beam separator deployed in CEBAF for delivering bunches to different experimental halls simultaneously [4]. Design-II, III and IV are the proposed crab cavity designs for the HL-LHC upgrade project [3]. Design-V is inspired from a NC RFD cavity design proposed in [5]. The original cavity designs had different operating frequencies, beam pipe radii, and aperture, in comparison to our requirements (table 1). Therefore, a substantial alteration in the geometry was carried out to obtain the deflecting mode at 260.5 MHz and also to meet the constraints. Instead of a tapered outer body for Design-IV, a straight cylindrical body was considered as suggested in [6]. The length of the cavity was fixed to $\lambda/2$ (575.8 mm) for all the five designs so that the maximum deflection can be achieved.

Eigenmode analysis using CST MWS® [7] was performed on all the designs. In each case, the EM field values were scaled such that a particle traversing on-axis receives a transverse deflecting voltage of 300kV. Further, the field values are exported and processed in MATLAB [8] to obtain the FOM of the cavities. Quality factor, surface power loss density and power loss are calculated considering that the cavity is constructed of copper. The dimensions of the cavity and the FOM computed are tabulated in table 2.

The transverse deflecting mode field pattern differs considerably between Design I-II (Group-A) and Design III-V(Group-B). Group-A designs have a lower order mode (LOM) and in the deflecting mode, the Lorentz force experienced by a charged particle due to the electric and magnetic field is along the same transverse direction. However, LOM are absent in group-B designs, and the direction of Lorentz force experienced by the magnetic field is opposite to that of the electric field in the deflecting mode. Nevertheless, the transverse force exerted by the electric field is far greater than that of the magnetic field and there is a net transverse deflection.

Group-A designs have a higher $R_\perp/Q$ compared to group-B designs, however they have a low quality factor resulting in lower transverse shunt impedance. The transverse shunt impedance dictates the total RF power required for a given transverse voltage and accordingly, Design-V has a lower surface power loss for a transverse voltage of 300 kV. The peak surface electric field in a NC cavity is not as critical as

Table 2: FOM computed for the five probable designs using CST MWS. In each case, the electromagnetic fields have been normalized to obtain a transverse voltage of 300 kV.

	Parameter	Notation	Unit	Design-I	Design-II	Design-III	Design-IV	Design-V
	Cavity width	l_x	mm	575.8	310.2	440.7	287.9	287.9
	Cavity height	l_y	mm	575.8	310.2	440.7	345.6	221.6
	Cavity length	l_z	mm	575.8	575.8	575.8	575.8	575.8
Deflecting mode	Mode frequency	f_{def}	MHz	260.5	260.5	260.5	260.5	260.5
	Transverse R/Q	$R_\perp/Q$	Ω	10495	9103	2278	1693	5746
	Quality factor	Q	-	7961	8490	15788	14908	14479
	Peak surface electric field	E_{peak}	MV m^{-1}	3.151	3.072	2.057	1.577	2.741
	Peak surface power density	S_{peak}	W cm^{-2}	4.64	4.82	2.28	1.48	1.34
	Total surface power loss	P_{loss}	kW	1.077	1.165	2.503	4.525	1.082
LOM	Mode frequency	f_{LOM}	MHz	209.5	204.2	-	-	-

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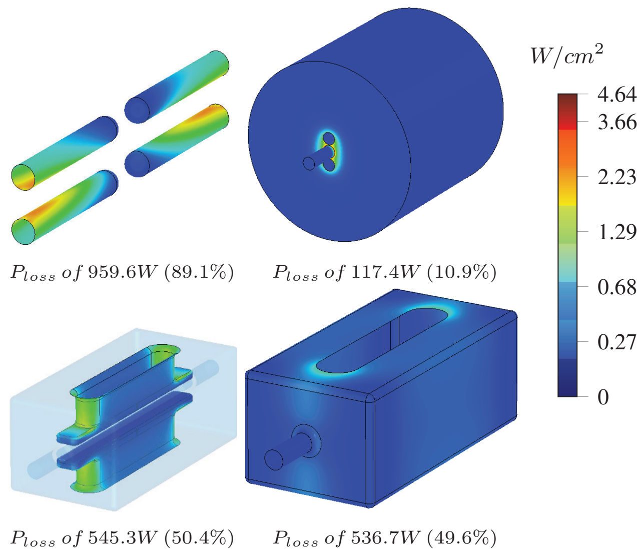

Figure 3: Distribution of the surface power loss on the inner (left) and outer part (right) of the cavity for Design-I (top) and V (bottom).

for a SC cavity. In any case, the peak surface electric field of all the designs satisfy the Kilpatrick's factor (16.35 MV m^{-1}) to avoid RF breakdown.

SURFACE POWER LOSS

The surface losses from a NC cavity need to be removed continuously through air or water cooling. The part of a cavity which requires cooling is decided based on the surface loss density distribution and the peak surface loss density dictates rate of cooling. If the RF loss is confined to a smaller area, then cooling this part is crucial. The total surface power loss for Design-I, II and V is around $\approx$1 kW. The surface power loss distribution for Design-I and V is shown in Fig. 3. Maximum power loss is concentrated in the four circular rods for Design-I and cooling these rods is very critical. Although the RFD cavity of Design-I is being operated in CEBAF without any thermal issues, for ELBE, we would envisage to operate the cavity at higher transverse voltage and this design would pose serious cooling issues. Equal proportion of power is distributed in the inner and outer cavity parts of Design-V, and this in turn relaxes the cooling requirement.

TRANSVERSE KICK HOMOGENEITY

Another critical requirement from the beam dynamics point of view is to have a transverse kick homogeneity of $\leq$ 0.15% in the good field region (GFR) of 5 mm radius around the beam axis. The transverse kick error in a 10 mm circular region around the beam axis for Design-V is plotted in Fig. 4. The relative transverse voltage error increases for an off-axis beam and it is prominent along the x and y-axis. Interestingly, the relative transverse voltage variation pattern is identical for the other designs as well. Variation of the transverse voltage error for all the five designs is shown in

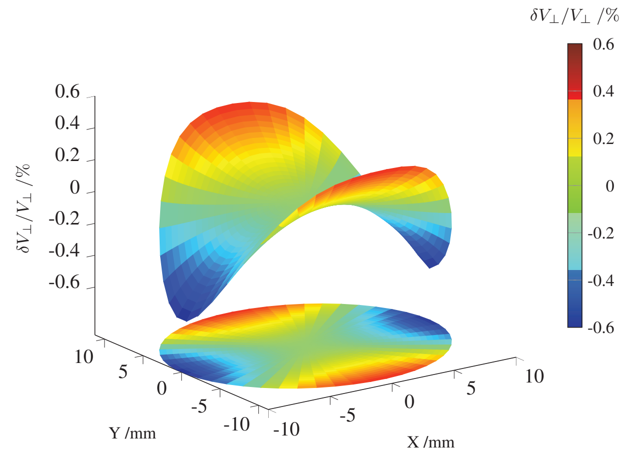

Figure 4: The relative transverse voltage variation in the circular region of radius 10 mm around the axis of the cavity forDesign-V.Thebeamtraversealongthe$z$-axis.

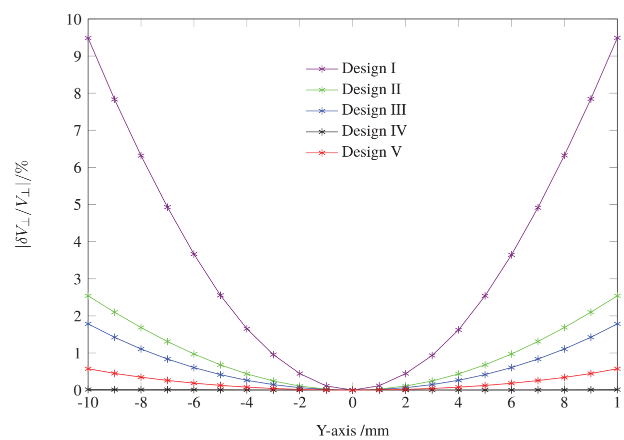

Figure 5: Relative transverse voltage variation along the y-axis for all the five cavity designs.

Fig. 5. Design-I has a lower field inhomogeneity as the rods are circular and an improvement is noticeable for Design-II for the kidney shaped rods. Further, flat surfaces improve field homogeneity in Design-III-V. The large elliptical flat parallel surface of Design-IV gives a superior field homogeneity compared to the other designs.

CONCLUSION

Numerical simulations were carried out on the five RFD cavity designs and FOM were computed. The total surface power loss for Design-I, II and V was $\approx$ 1 kW which was significantly lower than the other designs. However, Design-V has lower peak surface power density and proportionate surface power loss distribution resulting in less stringent cooling requirements. Furthermore, a better transverse kick field homogeneity in the GFR was observed for Design-V. Results from this numerical study suggest that Design-V is a preferred choice as a beam separator for ELBE.

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