

DESIGN OF A NORMAL CONDUCTING RF-DIPOLE DEFLECTING CAVITY*

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Abstract

Deflecting cavity is widely used in accelerators to provide transverse kick for beam separation, injection/extraction, bunch rotation, emittance exchange, etc. In this paper, we present the design of a normal conducting rf-dipole deflecting cavity. It is inspired by the recent development of compact superconducting crab cavity for LHC luminosity upgrade. Compared with superconducting cavity, normal conducting cavity has less constraints on geometry and peak surface field, thus has more design freedom to achieve higher $(R/Q)_T$ to compensate the surface ohmic loss. Depending on the cavity requirement, considering the economic cost and technology readiness, the normal conducting rf-dipole deflecting cavity can be an alternative choice of its superconducting counterpart.

INTRODUCTION

The deflecting cavity kicks the beam in transverse direction for beam separation, injection/extraction, bunch rotation, emittance exchange, etc. Traditional deflecting cavity uses the TM_{110} mode in the pillbox cavity as the deflecting mode. In recent years, a compact Superconducting (SC) rf-dipole (RFD) deflecting cavity [1] has been developed for LHC luminosity upgrade. The deflecting TE_{11} -like mode is the lowest frequency mode in the cavity, thus there is no need to separate the degenerated modes and easier to damp the unwanted modes. It also has a significantly higher $(R/Q)_T$ than the pillbox cavity. Inspired by this design, we have applied the similar concept to a Normal Conducting (NC) deflecting cavity. The NC material has less constraints on the geometry and peak surface field, thus gives us more freedom on the cavity design to increase $(R/Q)_T$ and compensate the surface ohmic loss. There is no need for sophisticated SC RF coupler, High Order Mode (HOM) damper and the cryogenic system. If operated under Continuous Wave (CW) mode, the maximum kicking voltage of this NC RFD cavity is limited by the peak surface power density.

In this report, we will first briefly go over the general merits calculation of a deflecting cavity, then present the conceptual design of a NC RFD, exploring how the cavity geometry parameters effect its RF performance and how to minimize the peak surface powder density. We will also give a design example of a 139 MHz deflecting cavity.

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MERITS OF DEFLECTING CAVITY

In the same way as accelerating cavity, the efficiency of deflecting cavity can be represented by:

$$(R/Q)_T = \frac{R_T}{Q_0} = \frac{V_T}{2\pi U f_0}, \quad (1)$$

where V_T is the effective transverse kicking voltage, U is the stored energy in the cavity and f_0 is the resonant frequency. Like the (R/Q) for the accelerating cavity, this merit depends only on the cavity geometry. For the ideal pillbox TM_{110} cavity with the length of $\lambda/2$, $(R/Q)_T \approx 64.07\Omega$. There are two ways to calculate V_T , one with Panofsky-Wenzel theorem and the other with Lorentz force directly.

Calculate V_T by Panofsky-Wenzel theorem

The Panofsky-Wenzel theorem [2]:

$$P_{\perp} = \frac{e}{\omega} \int_z (-i) \nabla_{\perp} E_z dz, \quad (2)$$

relates the transverse impulse with the transverse gradient of the longitudinal electric field. It shows pure TE mode cannot contribute to the transverse kick since there is no longitudinal E field. Thus we only need to consider TM mode, whose E_z can be expressed as:

$$E_z(r, \phi) = E_0 J_m(\gamma_{mn} r) e^{\pm im\phi}.$$

For RF deflecting cavity, the effective kick is along the radian direction of a particular ϕ_0 , thus we can simplified the 2D problem into 1D, with:

$$E_z(r) = E_0 J_m(\gamma_{mn} r),$$

and

$$\nabla_{\perp} E_z(r) = \nabla_r E_z(r) = E_0 \gamma_{mn} J'_m(\gamma_{mn} r).$$

Near $x=0$, Bessel function has the property:

$$J'_a(x) \approx J_a(x) \cdot \frac{a}{x},$$

thus:

$$\nabla_{\perp} E_z(r) \approx E_0 \gamma_{mn} J_m(\gamma_{mn} r) \frac{m}{\gamma_{mn} r} = E_z(r) \frac{m}{r},$$

and the transverse kicking voltage can be calculated from the longitudinal kick by:

$$\begin{aligned} V_{\perp} &= P_{\perp} \cdot c/e = \frac{e}{\omega} \int_0^L (-i) \cdot E_z \cdot \frac{m}{r} dz \cdot c/e \\ &= -i \frac{mc}{\omega r} \int_0^L E_z dz = -i \frac{mc}{\omega r} \cdot V_{\parallel} \end{aligned}$$

In a deflecting cavity, the dominate modes are of $m=1$, so:

$$V_{\perp} = -i \frac{c}{\omega r} \cdot V_{\parallel} \quad (3)$$

Equation 3 is based on two approximations: keeping only the first order of the Taylor expansion and excluding all the $m \neq 1$ modes. It gives a close estimation of the deflecting voltage.

Calculate V_T by Lorentz force

The transverse kick can also be calculated directly form Lorentz force. Assuming the kicking is in y direction:

$$V_y = \int [E_{y0} \cos(\omega z/c) - cB_{x0} \sin(\omega z/c)] dz,$$

where $E_y = E_{y0}e^{-i\omega t}$ and $B_x = -iB_{x0}e^{-i\omega t}$ are the transverse EM fields in the cavity. In our simulation, the RF field is solved by Omega3P [3]. Then V_{\perp} is calculated by Lorentz force and then checked by Equation 3.

CONCEPTUAL DESIGN OF A NC RFD DEFLECTING CAVITY

The design concept of a NC RFD deflecting cavity is to modify the SC RF-dipole like cavity to increase the cavity kicking efficiency $(R/Q)_{\perp}$ and reduce the surface peak power density.

To increase the $(R/Q)_{\perp}$, the most effective way is to reduce the distance between two dipole poles h . In such a resonant structure, the E field is mainly aligned between the two poles, while the B field is circulating around the poles. The smaller the distance between the two poles, the higher the local E field energy density, thus larger the transverse E field and $(R/Q)_{\perp}$. The limit of h value is determined by the required beam aperture. Figure 1 shows the E field pattern in the cavity and how $(R/Q)_{\perp}$ increases with the reduction of h .

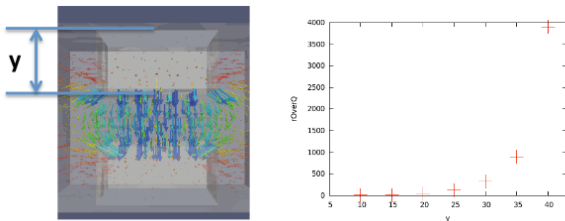


Figure 1: The left figure shows the E field plot in the RFD cavity. The right figure shows the relation between $(R/Q)_{\perp}$ and y , where y is the height of the poles. With fixed cavity total height H , the distance between two poles $h = H - 2y$. The shorter h corresponds to larger $(R/Q)_{\perp}$. For small h value, it is about inversely proportional to $(R/Q)_{\perp}$, if we treat the central region as a pair of parallel capacitor planes

Another way to increase the $(R/Q)_{\perp}$ is to decrease the B field in the center. As pointed out in [1], in the SC crab

cavity the B field kicks the beam in the different transverse direction of E field, thus the overall kicking effect is reduced. To suppress this negative effect from B field, we extend two "ears" at the pole ends, as shown in Figure 2, to trap the B field around the stub and prevent it from entering the central region. The simulation result, as shown in Figure 2, shows the increase of $(R/Q)_{\perp}$ as the length of pole ears extends. The Figure 3 shows the B field pattern in the cavity with the ear extensions.

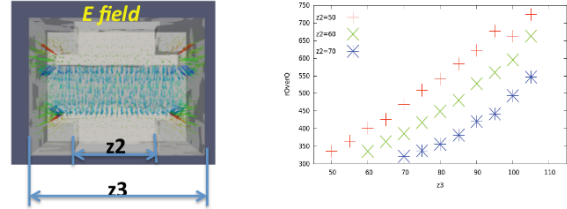


Figure 2: The left figure shows the E field in the cavity, with ear extensions at both ends of the poles, where z_2 is the length of the pole stub and z_3 is the total length of the pole including the ear extension. The right figure shows the simulation result of $(R/Q)_{\perp}$ vs z_3 with different z_2 values.

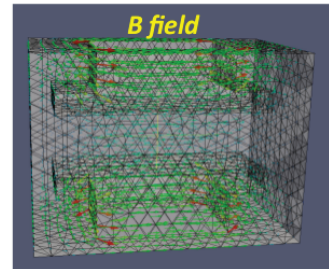


Figure 3: The B field pattern in the RFD cavity, with pole ear extensions. The major part of the B field is trapped around the stub and only a small portion penetrates into the central region. The maximum B field is located along the four corners of each stub.

To operate a NC RF cavity in CW mode with high power, surface ohmic heating is a major limiting factor on the achievable gradient. The surface power density is:

$$\frac{dP_{diss}}{dA} = \frac{1}{2\sigma\delta} H_{\theta}^2 = \frac{1}{2\sqrt{2}} \sqrt{\frac{\omega_0\mu_0}{\sigma}} H_{\theta}^2,$$

where σ is the surface conductivity, H_{θ} surface parallel H field, and skin depth $\delta = \sqrt{2/(\omega_0\mu_0\sigma)}$. As shown in Figure 3, the maximum B field is located along the four corners of each stub, thus rounding and smoothing treatment is required at these locations to reduce the maximum surface power density. Also such cavity is more suitable to work at low frequency, since $dP_{diss}/dA \propto \sqrt{\omega_0}$.

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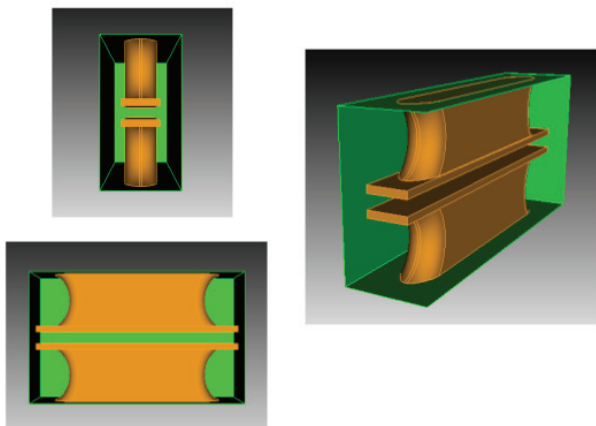


Figure 4: A example of NC RFD deflection cavity: 139 MHz deflecting cavity for NGLS beam spreader.

AN EXAMPLE: DEFLECTING CAVITY FOR NGLS BEAM SPREADER

To see how this concept works, we apply it to a real cavity design: the deflecting cavity for the beam spreader of Next Generation Light Source (NGLS) [4]. It requires a CW 9.6 MV kicking voltage within 2 m space. The geometry optimization is carried out for higher kicking voltage and lower surface power density. The optimized cavity structure is shown in Figure 4. For a 3.2 MV kicking voltage (thus need 3 cavities in series), we calculate the cavity parameters as shown in Table 1. The $(R/Q)_\perp$ has been increased significantly and the peak surface power density is controlled under $25\text{W}/\text{cm}^2$. The EM field patterns are shown in Figure 5. The transverse kick at $\pi/2$ crossing (maximum kick) and zero crossing (zero kick) along the central beamline is plotted in Figure 6. The major kicking force is the electric force, and the small magnetic force now kicks in the same direction with the electric force. Due to the parallel plane geometry and the relatively large surface area of the poles, the kicking field shows good uniformity along the beam path: the field variation is within 0.2% over a $14\text{mm} \times 14\text{mm}$ cross section.

Table 1: Cavity Parameters

| parameters | value | unit |
|---------------------|------------------|------------------------------|
| Frequency | 139 | MHz |
| Next frequency | 211 | MHz |
| $(R/Q)_\perp$ | 42613 | Ω |
| Power | 28.6 | kW |
| Peak dP_{diss}/dA | 21.7 | W/cm^2 |
| Total length | 500 | mm |
| Cross section | 180×340 | $\text{mm} \times \text{mm}$ |
| Total gap | 20 | mm |

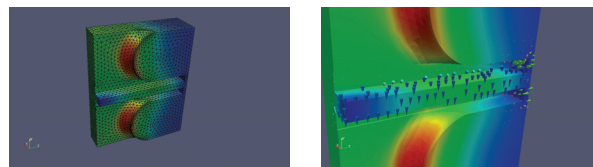


Figure 5: The RFD deflecting cavity design for NGLS beam spreader. The left figure shows a quarter of the whole structure, with the color code representing the strength of surface B field. The right figure shows the E field, visualized by small cones, in the central region.

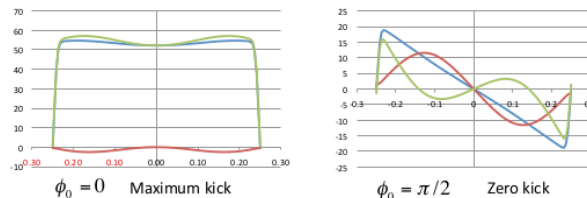


Figure 6: The transverse kick the particle experience along the central beamline. The left figure corresponds to the maximum kick, while the right figure the zero net kick. The blue curve is the electric kick, the red the magnetic kick and the red the total kick.

CONCLUSION

We present a design of NC RFD deflecting cavity inspired by the similar SC cavity. Utilizing the robustness of NC material, we modify the cavity geometry to increase $(R/Q)_\perp$ significantly to compensate the ohmic heating loss. The corners of the pole stub are rounded and smoothed to reduce the peak surface power density. When the required RF frequency is low and the beam aperture is small, this cavity can be an alternative choice of its superconducting counterpart.

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