STANDING WAVE RF DEFLECTORS WITH REDUCED ABERRATIONS *

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Abstract

Deflecting structures are now widely used for bunch phase space manipulations either to rotate a bunch for diagnostics purposes or in emittance exchange concepts. Even though the field of the synchronous harmonic is aberration free, the higher spatial harmonics provide nonlinear additions to the field distribution, leading to emittance growth during phase space manipulation. For short deflectors Standing Wave (SW) operation is more efficient. The criterion to estimate the field quality is developed and applied in order to minimize aberrations in the total deflecting field. The solution for dispersion correction together with the optimization of the end cells is described too.

INTRODUCTION

Deflecting Structures (DS), originally introduced for bunch deflection and particle separation [1], are now mainly used to rotate a bunch either for short bunch longitudinal diagnostics, [2], or in emittance exchange optics or to increase the luminosity. For deflection the bunch center crosses the DS at the maximal deflecting field, i.e. $\phi = 0$, while for bunch rotation $\phi = 90^o$ is used.

Modern DS applications are transformations of particle distributions in six-dimensional phase space. A tool for a transformation should provide as minimal as possible distortions of the original distribution.

The framework for the treatment of deflecting fields has been laid in the 60's by introducing the basis of hybrid HE and HM waves, [4], [3], and some results and conclusions, with certain assumptions and approximations, have been derived.

Even the synchronous harmonic of a deflecting field is inevitably nonlinear. The nonlinearity vanishes with $\beta \rightarrow 1$ and the aberration free, ideal case is reached for $\beta = 1$ only. But in the total DS field are always higher spatial harmonics which are by their nature nonlinear. The nonlinear terms lead to emittance growth during phase space manipulations, which can become important for precise measurements of very low emittance beams, or in case of multiple DS crossing.

FIELD DISTRIBUTIONS ANALYSIS

A recipe for estimates of field aberrations can be based on the general properties of periodicity and linearity, [5]. In any periodical structure the distribution of each field component $E_j(r,z)$ in the beam aperture can be represented in the complex form

$$E_j(r,z) = \widehat{E_j(r,z)} e^{i\psi_j(z)} = \sum_n^n a_{jn}(r) e^{\frac{-i(\Theta_0 + 2n\pi)z}{d}}, \quad (1)$$

where $\widehat{E_j(r,z)}$ and $\psi_j(z)$ are the amplitude and phase distributions, $d = \frac{\Theta_0 \beta\lambda}{2\pi}$ is the structure period, $a_{jn}(r)$ is the transverse distribution of the n-th spatial harmonics and Θ_0 is the phase advance. Spatial harmonics are essential at the aperture radius $r = a$ while higher harmonics attenuate toward the axis as

$$a_{jn}(0) \sim a_{jn}(a) \cdot exp(-\frac{4\pi^2 n}{\beta\Theta_0} \cdot \frac{a}{\lambda}), \quad |n| \gg 1, \quad (2)$$

where λ is the operating wave length. To estimate the harmonics in detail and 'in total', we use the parameters $\delta\psi_j(z)$ and Ψ_j at the axis $0 \leq z \leq d, r = 0$, [5]

$$\delta\psi_j(z) = \psi_j(z) + \frac{\Theta_0 z}{d}, \quad \Psi_j = max(|\delta\psi_j(z)|). \quad (3)$$

The total force on a charged particle - the Lorenz force

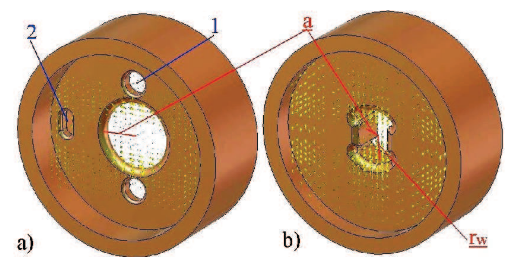

Figure 1: Structures with the minimized E_d aberrations, the optimized DLW structure (a) with holes for deflecting plane stabilization (1) and slots for dispersion correction (2) and the decoupled structure (b).

$\vec{F}^L$ - can be split in Cartesian coordinates into the longitudinal eE_z and the transverse eE_d components, assuming deflection in x direction,

$$\vec{F}^L_{z,x} = eE_z\vec{z}_0 + eE_d\vec{x}_0, E_d = E_x - \beta Z_0 H_y, Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}. \quad (4)$$

Parameter Ψ_j can be used to estimate the level of harmonics (aberrations) both in the longitudinal eE_z, Ψ_z and in the transverse eE_d, Ψ_d force component.

The structures, obtained by optimizing aberrations, are shown in Fig. 1. Besides the well-known Disk Loaded Waveguide (DLW), Fig. 1a, a decoupled deflecting structure has been optimized. This structure follows the design idea of separated functions, see [6] for details.

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ABERRATION REDUCTION FOR DLW

The attenuation (2) works both for E_z and E_d at low values of Θ_0 in the Traveling Wave (TW) regime in any structure, even for small aperture radii, [5], [6]. For SW

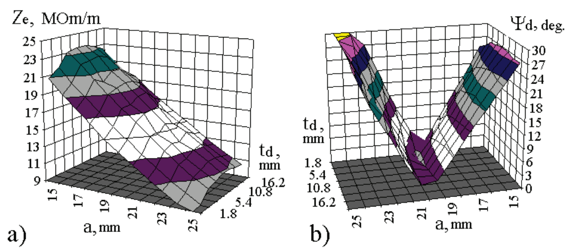

Figure 2: The surfaces $Z_e(a, t_d)$ (a) and $\Psi_d(a, t_d)$ (b) for the DLW structure, $\lambda = 10cm, \Theta_0 = 180^o$

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operation, $\Theta_0 = 180^o, (= \pi)$, the attenuation is not effective and the field components have a higher aberration level as compared to the TW mode. The longitudinal force F_z^L is generated by a single field component E_z and an essential aberration reduction is not possible. For a precise transformation of the longitudinal distribution a TW mode is preferable.

The transverse component F_x^L is composed of two components, and the mutual phasing of E_x and H_y is crucial. For opposite phasing the synchronous harmonics components E_x^0 and $Z_0 H_y^0$ contribute in (4) together to the deflection, but the higher harmonics in E_x and H_y partially compensate, leading to an aberration reduction in E_d.

In Fig. 2 surfaces of $Z_e(a, t_d)$ and $\Psi_d(a, t_d)$ for the DLW structure are shown, where t_d is the disk thickness and Z_e is the effective shunt impedance. It can be seen that for every value of t_d a value of a exists which realizes $\Psi_{d(min)} \sim 2^o$, corresponding to $a_{dn}(0) \sim 10^{-2}$ in contrast to $a_{d1}(0) \sim 0.4, a_{d2}(0) \sim 0.1$ for other DLW cases. The optimum of $\Psi_{d(min)}$ a_{opt} slightly rises with increasing t_d: $a_{opt} = 19.41mm$ for $t_d = 5.4mm$ and $a_{opt} = 20.54mm$ for $t_d = 10.8mm$. The DLW RF efficiency, Z_e, decreases with increasing a and has a shallow maximum at $t_d \sim 9.8mm$, Fig. 2a. As compromise for a SW DLW deflector with minimized E_d aberrations we chose $t_d = 8.1mm, a = 20.17mm$. Thus for classical DLW in SW mode the aberration reduction in the transverse F_x^L component can be achieved by a selection of the aperture radius, but on the expense of a moderate shunt impedance of $Z_e \sim 17\frac{MOm}{m}$.

DISPERSION CURVE CORRECTION

The opposite E_x and H_y phasing defines a negative dispersion of the DS. For an effective aberration reduction the amplitudes should be balanced, $|E_x^0| \sim |Z_0 H_y^0|$. But this balance can be obtained only in the vicinity of the inversion point with $\beta_g = 0, \Theta_0 < 180^o$, [5]. Cavities with minimized aberrations have therefore a narrowed operating passband with not large frequency separation near the operating mode.

To improve the frequency separation, we apply the resonant method, proposed for deflecting plane stabilization in DLWs, [7]. One resonant slot (2 in Fig. 1a) with eigenfrequency f_s much higher than the operating frequency f_0 is introduced into the disk to interact with the modes of the operating deflection direction. The intensity of the slot excitation depends on both f_s and Θ of the cavity mode. The mode frequency shift, caused by the slots, is $\delta f \sim \frac{(sin\frac{\Theta_0}{2})^2}{f_s^2 - f_0^2}$, resulting in a better frequency separation near the operating mode $\Theta_0 = \pi$. To provide a larger δf with smaller slot excitation and avoid that $E_z \neq 0$ at the deflector axis, slots in adjacent disks are rotated by 180^o. For the optimized DLW the application of the slots improves the frequency separation by 1.4 times the number of periods in the cavity $N = (4 \div 8)$.

The same approach can be applied for the correction of the dispersion curve distortions in low Θ_0, low β_g TW DLWs, [5], operating with minimal E_z and E_d aberration

END CELLS

The input/output end cells with the connected beampipes deteriorate the periodicity of the structures and cause a transverse kick of the bunch. The field penetrating into the beampipe decays away from the cavity but provides an initial transverse kick. To reduce this part of the deflection and thus simultaneously reduce the total kick the beampipe radius should be as small as reasonably possible. The end cells together with the beampipe can be tuned to the operating frequency as separate units by adjusting the cell radius r_{ce} while keeping the boundary condition $E_\tau = 0$ in the middle of the iris connecting to the periodic structure. This ensures that the frequency and the field distribution are independent of the number of regular cells.

By changing the length L_e of the end cell the distribu-

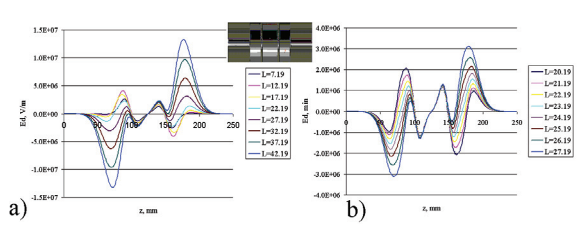

Figure 3: Distribution of E_d at $\phi = 90^o$ for various end cell length L_e in a broad range (a) and tuned around for $Int_{1t}(z) = 0$ (b).

tion of E_d can be changed in a wide range, Fig. 3. The transverse field can be reduced but does not disappear completely. The transverse kick is however proportional to the first field integral $Int_{1t}(z)$

$$Int_{1t}(z) = \int_{-\infty}^{z} E_d(z', \phi = 90^o) dz'. \quad (5)$$

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The condition $Int_{1t}(z) = 0$ results in a reduced variation of $E_d, \phi = 90^o$ in the end cell, comparable to the residual $E_d, \phi = 90^o$ variation in the regular cells, see Fig. 3, and a minimized kick in the end cells.

DECOUPLED STRUCTURE

The designer of a DLW structure has effectively only one degree of freedom - the aperture radius which defines simultaneously both the $E_x and H_y$ amplitudes and balance. Thus a high RF efficiency with minimized aberrations cannot be achieved simultaneously. The possibility to control both the E_x and H_y phasing and balance demonstrated for a TE - type deflector [6] allows to design an effective DS with a strong transverse electric field, a positive dispersion due to the same E_x and H_y phasing and decoupled control of RF efficiency and coupling. As shown in [6], the E_x and H_y amplitudes, phasing and balance depend on the combination of $a - r_w$, see Fig. 1b.
Choosing the aperture radius a as small as possible a high shunt impedance Z_e is realized due to a strong E_x component. Reducing the window radius r_w the difference in the phasing of E_x and H_y increases from the equal phasing as in the original design through the point with $H_y^0 = 0$ to the opposite phasing, where the compensation of aberrations becomes possible. Continuing to reduce the window radius the balance $|E_x^0| \sim |Z_0 H_y^0|$ with minimized E_d aberrations is obtained. During this transformation the shunt impedance Z_e reduces but still remains higher as compared to a DLW. The obtained field distribution is shown in Fig. 1b and there is indeed no reason to name the obtained structure TE - like. As a result we have a very flexible solution which allows to combine a high shunt impedance $Z_e > 30\frac{MOm}{m}$ with minimized aberrations $\Psi_{d(min)} \sim 2^o$ and different $|E_x^0|, |Z_0 H_y^0|$ balance.

DEFLECTING CAVITIES

In Fig. 4 the field distributions for the same stored energy of different SW deflectors are shown: The optimized DLW, (Fig. 4a) with $\frac{Z_0 H_y^0}{E_x^0} = 0.8549, \Psi_d = 2.39^o$ and two options of decoupled structures with $\frac{Z_0 H_y^0}{E_x^0} = 0.7904, \Psi_d = 2.07^o$, Fig. 4b, and $\frac{Z_0 H_y^0}{E_x^0} = 1.0008, \Psi_d = 2.10^o$, Fig. 4c . Strongly reduced residual $E_d, \phi = 90^o$

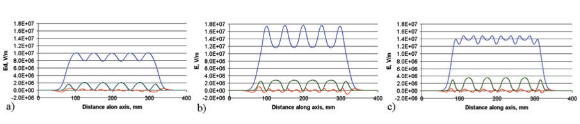

Figure 4: The field distributions along the deflector axis for the optimized DLW, (a) and two decoupled structures, (b) and (c). Blue - $E_d, \phi = 0^o$, red - $E_d, \phi = 90^o$, green - $E_z, \phi = 90^o$

oscillations inside the cavity together with a reduced input kick in the end cells can be seen. Because the quality factors for the deflectors are comparable, the decoupled structure provides a higher deflecting field. For the deflector length of $\sim 20cm$, meaning two regular cells, RF coupler cells and two end cells, the calculated total shunt impedances are $2.84MOm, 4.57MOm$ and $6.04MOm$, respectively.
The technical solutions for the SW deflectors are shown in Fig. 5

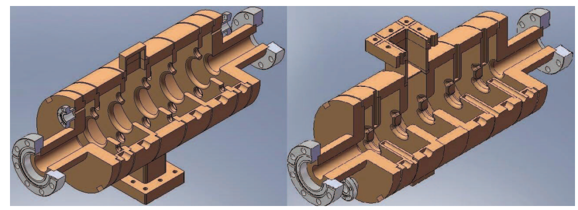

Figure 5: Deflectors with minimized E_d aberrations, the optimized DLW (left) and the decoupled structure (right).

SUMMARY

Different standing wave deflectors are considered for applications in bunch rotation with the aim to reduce distortions of the incoming particle distribution by minimizing aberrations in the effective force. For a SW operating mode aberration minimization in the longitudinal force component is not significant. For the transverse force component a strong reduction of the aberration is achieved by appropriate balancing of transverse field components. For the well-known DLW structure a reduction of aberrations is achievable at the expense of RF efficiency. A flexible solution - a decoupled deflecting structure - is described to combine high RF efficiency with minimized aberrations for different field distributions. A publication containing more detailed descriptions of field distributions and beam dynamics results including numerical simulations is in preparation.

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