DEFLECTING STRUCTURES WITH MINIMIZED LEVEL OF ABERRATIONS*

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Abstract

Deflecting structures are now widely used for bunch phase space manipulations either in special bunch diagnostic or in emittance exchange experiments. As a tool for manipulation, the structure itself should provide the minimal phase space perturbations due to non linear additives in the field distribution. Criterion of the field quality estimation is developed and deflecting structures are considered for minimization of non linear additives.

INTRODUCTION

The Deflecting Structures (DS) - periodical structures with transverse components of the electromagnetic field - initially were introduced for charged particle deflection and separation. The bunch cross DS synchronously with the deflecting field Ed, corresponding the phase $\phi = 0$ in the structure and particles get the increment in the transverse momentum p_t. There are a lot of papers, see for example [1], describing DS design and application for such purpose. At present for short and bright electron bunches DS found another applications, either for bunch special diagnostic, [2], or emittance exchange experiments. Both directions are related to the transformation of particle distributions in the six dimensional phase space and DS operates in another mode - the bunch center cross DS at zero E_d value, $\phi = 90^o$. There are also a lot of papers, describing it in more details. Application for Particles Distributions Transformation (PDT) provide additional requirements - a tool for transformation should provide the minimal, as possible, own distortions to the original distributions.

FIELD DISTRIBUTION QUALITY

For deflecting field E_d description the widely used basis of $TM-TE$ waves can not be used due to degeneration into TEM at $\beta = 1$. A basis of hybrid waves $HE - HM$ was introduced, [3], [4] to avoid this methodical problem. The common representation for the field distribution in the DS aperture is

$$\vec{E} = C\vec{E}_{HE} + D\vec{E}_{HM}, \quad \vec{H} = C\vec{H}_{HE} + D\vec{H}_{HM}, \quad (1)$$

with the weighting coefficient C, D depending both on supporting structure and on operating mode. It is the method of description and results treatment. The physical object - the deflecting force - is the transverse component of the Lorenz force

$$\vec{F}^L = e(\vec{E} + [\vec{v}, \vec{B}]), F_x = eE_d = e(E_x - \beta Z_0 H_y), \quad (2)$$

where $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$, expressed in (2) through the transverse E_x and H_y components in Cartesian coordinates.
In any periodical structure for Traveling Wave (TW) operating mode each field component $E_j(r, z)$ in the beam aperture can be represented in the complex form as the set over spatial harmonics:

$$E_j(r, z) = \widehat{E_j(r, z)} e^{i\psi_j(z)} = = \sum_{n\to-\infty}^{n\to+\infty} a_{jn}(r) e^{\frac{-i(\Theta_0+2n\pi)z}{d}}, \quad (3)$$

where $\widehat{E_j(r, z)}$ and $\psi_j(z)$ are the amplitude and the phase distributions, d is the structure period and $a_{jn}(r)$ is the transverse distribution for the n-th spatial harmonics. The period length is defined from synchronism with the main a_{j0} harmonic, $d = \frac{\Theta_0\beta\lambda}{2\pi}$.
The bunch emittance deterioration during PDT take place due to non linear additions both in transverse and longitudinal distributions of the field. There is inevitable nonlinearity at $\beta < 1$ even in main harmonic distribution, vanishing for $\beta \to 1$, [3], [5]. But the main source of additions are higher spatial harmonics. For each harmonic the transverse and longitudinal distributions are rigidly coupled and are proportional to harmonic amplitude. To estimate field quality, we have to estimate the level of spatial harmonics, [5]. Spatial harmonics are essential at the aperture radius $r = a$ and higher harmonics attenuate to the axis as

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

where λ is the operating wave length. At the axis $r = 0$ just lower harmonics $n = \pm1, \pm2, \pm3$ are really presented. For harmonics estimations in details and 'in total', let us introduce parameters $\delta\psi_j(z)$ and Ψ_j at the axis $0 \le z \le d, r = 0$

$$\delta\psi_j(z) = \psi_j(z) + \frac{\Theta_0 z}{d}, \quad \Psi_j = max(|\delta\psi_j(z)|), \quad (5)$$

with the physical sense as the deviation and the maximal phase deviation of the real wave component from the synchronous harmonic. The qualitative estimation and correct value for $a_{jn}(0)$ one can get as

$$|a_{jn}(0)| < \frac{(\widehat{E_j(0, z)}_{max} + \widehat{E_j(0, z)}_{min})\Psi_j}{2n}, \quad (6)$$

$$a_{jn}(0) = \frac{\int_0^d \widehat{E_j(0, z)} sin(\delta\psi_j(z)) sin(\frac{2\pi n z}{d}) dz}{d}.$$

From linearity, we can apply $\delta\psi_j(z)$ and Ψ_j for quality

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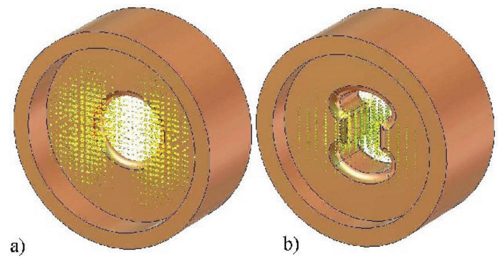

Figure 1: DLW (a) and TE - type (b) deflectors.

estimation both in longitudinal $E_z, \delta\psi_z(z), \Psi_z$ and transverse $E_d, \delta\psi_d(z), \Psi_d$ field components, also estimating PDT quality in these directions. To emphasize the differences in field distribution, the developed method is applied for analysis of DLW [6] and TE - type deflectors, Fig. 1.

OPERATING MODE

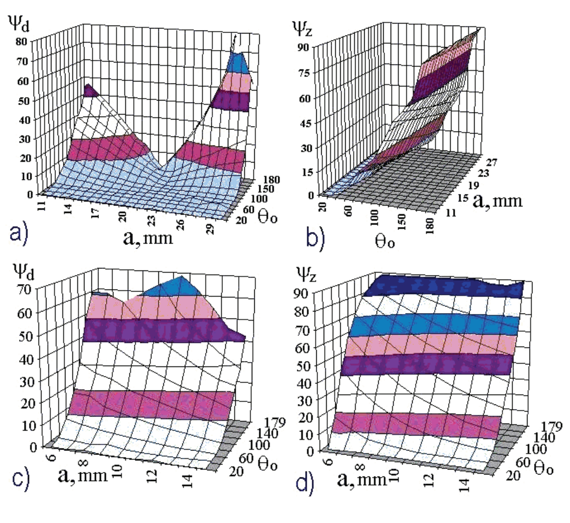

Figure 2: The surfaces $\Psi_d(a, \Theta_0)$ (a,c) and $\Psi_z(a, \Theta_0)$ (b,d) for the DLW (a,b) and TE - type (c,d) deflectors.

Assuming operating frequency $f_0 = 3GHz$, in Fig. 2 are shown the surfaces $\Psi_d(a, \Theta_0)$ and $\Psi_z(a, \Theta_0)$ for the DLW and TE - type deflectors both for TW $0 < \Theta_0 < 180^0$ and Standing Wave (SW, $\Theta_0 = 180^0$) operating mode,[5].

TW Operation

As can be seen from Fig. 2, small Ψ_d, Ψ_z values all time are at lower $\Theta_0 \leq 60^o$ values. For spatial harmonics the decrement of attenuation in (4) is inverse proportional to Θ_0 and $a_{zn}(0), a_{dn}(0)$ all time are small for low Θ_0. It is the common property of slow wave systems. Any periodical structure has reduced aberration level in TW operation with low Θ_0, both in E_z and in E_d distributions. For DLW harmonics attenuation is essentially stronger due to larger aperture radius.
Another effect is very important for E_d distribution and is in mutual phasing of transverse E and H components. For the opposite E_x and H_y phasing (DLW) electric and magnetic components work for deflection together (1), but E_x spatial harmonics compensate or even cancel $Z_0 H_y$ harmonics. It extends low Ψ_d region to higher Θ_0 values, Fig. 2a, and $\Psi_d < \Psi_z$. For the same E_x and H_y phasing (TE deflector) deflection form electric and magnetic components is partially compensated (1), but E_x and $Z_0 H_y$ harmonics add, $\Psi_d > \Psi_z$. The significant harmonics cancellation takes place at $|E_x^0| \sim |Z_0 H_y^0|$ - for comparable amplitudes of synchronous harmonics in E_x and H_y distributions. One can see clear canyon in $\Psi_d(a, \Theta_0)$ surface in Fig. 2a and for the bottom of this canyon $|E_x^0| \approx |Z_0 H_y^0|$. The structures with opposite phasing can provide very small aberrations level in E_d distribution.
In the Table 1 are listed the relative harmonics amplitudes for DLW TW operation. In comparison with DLW LOLA

Table 1: The relative $a_{zn}(0) \cdot 10$ and $a_{dn}(0) \cdot 10$ values for DLW.

Operation $a =, mm$	Θ_0	E_z, $n=1$	E_z, $n=2$	E_d, $n=1$	E_d, $n=2$
TW,23.80	60	-0.048	-0.007	0.006	-0.009
TW,23.58	90	-0.581	-0.004	0.009	-0.001
TW,22.33	120	-1.950	-0.048	0.020	-0.015
SW,12.0	180	-6.103	-1.385	-3.818	-0.623
SW,19.4	180	-5.619	-0.691	-0.271	-0.148

deflector, [6], or similar structures with $\Theta_0 = 120^o$, operation with $\Theta_0 = 60^o$ leads to aberrations reduction in times, especially for longitudinal force. Conditions for RF efficiency in TW case also are more flexible, as compared to SW case. The end cells with RF couplers are the points of special consideration, [5].

SW Operation

In the case of short deflectors SW operation is more efficient in RF sense. But individual E, H components, including E_z at $\Theta_0 = 180^o$ have a single, either real or imaginary part in representation (1), resulting in $\Psi_j = 90^0$ for each component separately. For longitudinal force aberration reduction is possible just by aperture radius increasing -it is not so effective as for low Θ_0 TW case.
The deflecting field E_d is composed from two components, E_x, H_y and has in representation (1) both real and imaginary parts, similar to TW case. Relations (5),(6) work for E_d study even for Θ_0 SW case.
Because harmonics attenuation at $\Theta_0 = 180^o$ (assuming $\beta = 1$) is not effective, the single way for aberration reduction in E_d is harmonics cancellation for E_x and H_y distributions under opposite phasing. It can be realized in DLW by aperture radius choice for the preliminary specified disk thickness t_d, [8]. In the Table 1 are given results for optimized SW case ($a = 19.4mm, t_d = 5.4mm, \Psi_d \sim 1.5^o$, $\frac{Z_0 H_y^0}{E_x^0} = 0.98$). In SW DLW E_d aberration reduction is possible, but at the expense of moderate RF efficiency.

SUPPORTING STRUCTURE

The hybrid HE_n, HM_n waves exist in a supporting RF structure. But the classification of a supporting structure with a complicated field distribution is always rather conditional. In Fig. 3 the plots of $\frac{Z_0 H_y^0}{E_x^0}$ balance are shown,

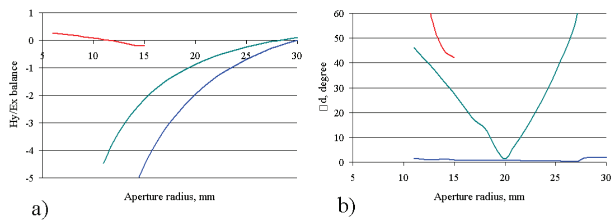

Figure 3: The field balance $\frac{Z_0 H_y^0}{E_x^0}$ (a) and $\Psi_d(a)$ plots (b) for DLW deflector $\Theta_0) = 60^o$ (blue), $\Theta_0) = 180^o$ (green) and TE - type deflector, $\Theta_0 = 180^o$ (red).

having even for well studied DLW in the first passband a large variety $-10 \leq \frac{Z_0 H_y^0}{E_x^0} \leq 0.5, 10mm \leq a \leq 30mm$ with different $\vec{E}, \vec{H}$ distributions, [5]. Similar field trans-

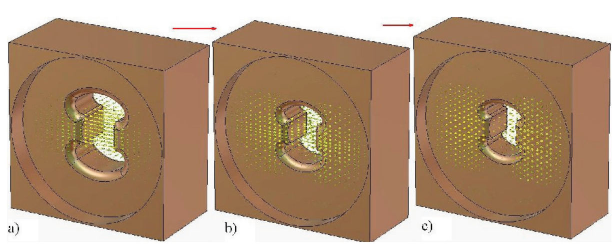

Figure 4: Field transformation for deflecting mode in the TE - type deflector.

formation we can provide in TE deflector, [7], Fig. 4.
At the structure axis we can define C, D in (1) from the already calculated E_d distribution and connect it with $\frac{Z_0 H_y^0}{E_x^0}$ balance. For E_d aberration minimization, especially for SW case, we need the opposite phasing of transverse $\vec{E}, \vec{H}$ components. Now it is the single sustainable sign for structure selection. Such phasing means the negative power flow near, but doesn't mean, in general, total negative flow, which define a negative dispersion in operating point. Even in simple DLW the inversion aperture radius a_i, corresponding to $\beta_g = 0$, essentially depends on Θ_0, [5].
For effective aberration reduction in E_d we need in the balance $|\frac{Z_0 H_y^0}{E_x^0}| \approx 1$. But the case of $|Z_0 H_y^0| = |E_x^0|$ is very close, probably coincides, to inversion point. It results in non monotonous (for TW case, [5]) or narrow (for SW case, [8]) dispersion curve. The method for DLW dispersion curve correction is described in [8]. Also the practice of Ψ_d minimization shows, that $(\Psi_d)_{min}$ is close, but not identical to $|Z_0 H_y^0| = |E_x^0|$ condition.

The DLW has just one parameter, effective for $\frac{Z_0 H_y^0}{E_x^0}$ balance control, aperture radius a, see Fig. 3a, which defines RF efficiency also. By splitting control over transverse $\vec{E}, \vec{H}$ components in TE - deflector, which is defined by r_a, r_w combination, see [7], we also can get opposite H_y and E_x phasing, Fig. 3a. Continuing the structure transformation, shown in Fig. 4, we come in the region $|Z_0 H_y^0| \approx |E_x^0|$ from the top in Fig. 3a. The field distribution becomes as in right picture in Fig. 3 and there are no evident reasons denote transformed option as TE-type. We lose in RF efficiency (Z_e value), as compared to original case, Fig. 1b, [7], but still remain essentially higher, as compared to simple DLW. The level of aberration is practically the same as for optimized in $(\Psi_d)_{min}$, see Table 1, case $a = 19.4mm$, classical DLW structure. The parameters of such SW deflectors in details, including end cells and RF coupler cell, are considered in [8].

SUMMARY

In any periodical DS aberrations, both in E_z and in E_d, are lowered in TW operation with $\Theta_0 \leq 60^o$, especially for large aperture radius. Essential improvement in E_d distribution also takes place for opposite phasing of transverse $\vec{E}, \vec{H}$ components at the axis. Such TW DS provide the best results in PDT linearity. For TW operation with $\Theta_0 \geq 120^o$ and SW, $\Theta_0 = 180^o$, aberration reduction is possible in E_d only, by aberrations cancellation in oppositely phased and balanced transverse $\vec{E}, \vec{H}$ components. In a simple SW DLW it is realized for moderate RF efficiency. By splitting control over transverse $\vec{E}, \vec{H}$ components we get efficient SW DS with low E_d aberration level.

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