ANALYSIS AND MODELING OF A STRIPLINE BEAM KICKER AND SEPTUM

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Abstract

A fast stripline beam kicker and septum are used to dynamically switch a high current electron beam between two beamlines. The transport of the beam through these structures is determined by the quality of the applied electromagnetic fields as well as temporal effects due to the wakefields produced by the beam. In addition, nonlinear forces in the structure will lead to emittance growth. The effect of these issues is investigated analytically and by using particle transport codes. Due to the distributed nature of the beam-induced effects, multiple macro-particles (slices) are used in the particle transport code, where each slice consists of an ensemble of particles with an initial distribution in phase space. Changes in the multipole moments of an individual slice establish electromagnetic wakes in the structure and are allowed to interact with subsequent beam macro-particles to determine the variation of the steering, focusing, and emittance growth during the beam pulse.

1 INTRODUCTION

The stripline kicker is designed to spatially separate a high current electron beam for transport into two separate beamlines. However, to provide a significant angular kick to the beam, a magnetic dipole septum is required. This system is shown schematically in Figure 1.

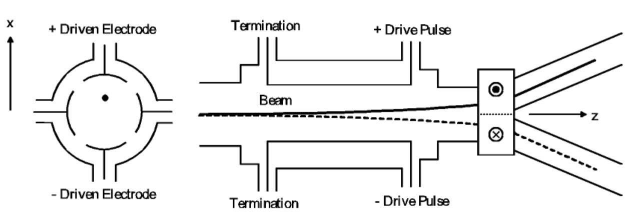

Figure 1 Kicker and septum configuration for dynamic beam steering in one plane

The operation of the system is as follows: A high voltage pulse is applied to the downstream ports of the kicker and the beam is spatially separated (kicked) by a combination of the transverse electric and magnetic dipole forces associated with the TEM waves propagating on the strip transmission lines. The beam is then directed into a septum magnet with opposite polarity dipole fields on either side of the plane separating the two downstream beam lines. All the upstream ports and the two downstream ports in the non-kick plane are terminated in a matched load impedance for the dipole transmission mode on the structure. It should be noted that steering in both planes can be accomplished by also driving the other pair of plates.

2 KICKER TEM FIELDS AND BEAM DEFLECTION

To steer the beam in *x*, opposite polarity high voltage pulses are applied to the downstream ports in the $y=0$ plane. The potential within the kicker plates ($r<b$) is given by

$$V = \frac{4V_p}{\pi} \sum_{m=odd} \left(\frac{1}{m}\right) \sin\left(\frac{m\phi_0}{2}\right) \cos(m\phi) \left(\frac{r}{b}\right)^m \quad (1)$$

where b is the interior radius of the kicker plates, and ϕ_0 is the angle subtended by the kicker plates. The voltage applied to the plate is V_p giving a total steering voltage of $2V_p$. The solution is determined by solving for the potential in the region $r<b$, and using the boundary condition that the potential at $r=b$ is given by the appropriate applied plate voltages and that the potential in the gaps between the plates is zero. The TEM fields can be easily derived from this scalar potential. The $m=1$ term in Equation (1) represents a transverse dipole force which provides the beam steering while the higher order terms will contribute to emittance growth in the beam. The beam deflection due to the combined electric and magnetic dipole forces is given by

$$\Delta x = \frac{\pi b V_p}{I_c Z_k \sin(\phi_0/2)} \quad (2)$$

where the critical current, I_c is defined by

$$I_c = \frac{\pi}{16} \frac{\gamma\beta^2 I_0}{\sin^2\left(\frac{\phi_0}{2}\right)} \frac{Z_0}{Z_k} \left(\frac{b}{L}\right)^2 \quad (3)$$

and I_0 = 17 kA, Z_0 = 377 Ω, L is the length of the kicker, b is the inner radius of the kicker plates, Z_k is the kicker impedance, and γ is the usual relativistic factor.

3 DIPOLE WAKE IMPEDANCE AND BEAM INDUCED STEERING

In our application, the beam current is sufficiently large as to induce substantial voltages and currents on the strip transmission lines. These voltages and currents are introduced on the transmission lines as the beam traverses the upstream and downstream gaps as well as from changes in the dipole return current as the beam is deflected. A detailed model has been previously described [1],[2]. The *m=1* transverse dipole wake impedance for this structure [3] is given by

$$Z_{\perp}(\omega)=\frac{8cZ_k}{\pi^2 b^2}\sin^2\left(\frac{\phi_0}{2}\right)\left(\frac{1}{\omega}\right)\left[\sin^2\left(\frac{\omega L}{c}\right)\right.$$
$$\left.+\,j\sin\left(\frac{\omega L}{c}\right)\cos\left(\frac{\omega L}{c}\right)\right]. \quad (4)$$

The imaginary part of the dipole impedance, $Z_{\perp 0}=\mathrm{Im}[Z_{\perp}(\omega=0)]$ is a measure of the asymptotic beam deflection due to the beam-induced fields. It has been shown that the asymptotic beam deflection for an initially offset beam with current I_B injected into the kicker has the form [1]

$$x_{\infty}=x_0\cosh\left(\sqrt{\frac{2I_B}{I_c}}\right) \quad (5)$$

where x_0 is the injection offset of the beam. It is easily shown for sufficiently small beam currents that

$$x_{\infty}\approx x_0\left[1+\left(\frac{2\pi L}{\gamma\beta^2 I_0 Z_0}\right)I_B Z_{\perp 0}\right]. \quad (6)$$

To examine the relevant physics issues, a kicker has been designed and installed on the Experimental Test Accelerator (ETA-II). The ETA-II kicker has the following set of parameters: b=12.87 cm, ϕ_0=78°, Z_k=50 Ω, L=164 cm and I_c=3.9 kA. The outer enclosure has a radius of 19 cm. To verify the validity of the transmission line model the structure was modeled using a 3-D time domain electromagnetic code to determine the dipole impedance spectrum. Figure 2 shows a comparison of the dipole impedance as calculated from Equation (4) with numerical results from a 3-D time domain electromagnetic code for the ETA-II kicker. As can be seen there is a good agreement between the transmission line model and the 3-D code results. The differences can be attributed to end cavity effects associated with the feeds to the external ports and effects due to higher order modes in the structure.

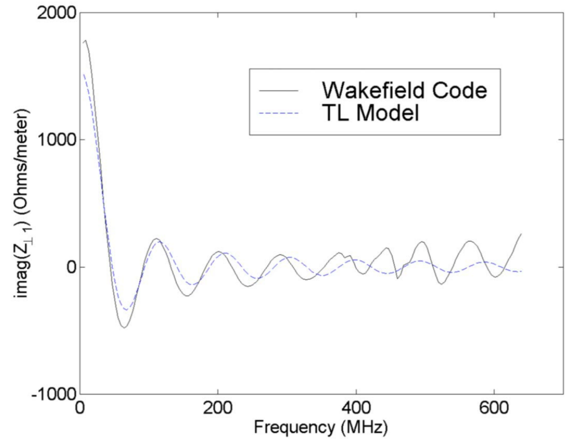

Figure 2 Dipole wake impedance

The effect of the wake impedance on the deflection of the beam can be quite dramatic. For example, for a 6 MeV, 2 kA beam initially offset by 2 cm going into the kicker, the tail of the emerging beam will be offset by 3.1 cm at the exit of the structure. These effects have been observed experimentally [4] and are consistent with theory.

4 NONLINEAR FORCES AND EMITTANCE GROWTH

From Equation (1) it is seen that for a dipole excitation of the kicker, all higher order odd multipoles will be excited in the structure. Although the higher order multipoles reduce in strength as $(r/b)^m$ it is possible under certain conditions that the beam will experience these fields, especially the *m=3* sextupole component. For example, with ETA-II parameters the space charge fields due to the beam may require that the beam entering the kicker have a large radius to enable the downstream beam to be at or near a waist when entering the dipole septum. This is important in order to minimize any emittance growth due to the nonlinear fields associated with the septum magnet. In order to estimate the effect of the higher order multipoles due to the kicker on the beam emittance, a simple particle transport code was developed. The code includes the external fields in the kicker region as defined by Equation (1) and is being expanded to include the beam-induced effects and space-charge effects self-consistently. Presently, the particles respond only to the external fields. However, we can estimate the emittance growth in the structure by using the external fields only. As an example, using the ETA-II kicker previously described, a 6 MeV beam is injected into the kicker with an unnormalized edge emittance of 13 cm-mrad and a convergence angle of .03 rad. The injected beam radius is 4 cm, which allows the beam to experience the higher order multipoles. Figure 3 shows a configuration space image of the emerging beam from the kicker showing a centroid location of 2.7 cm consistent with Equation (2). The triangular image has been observed experimentally [4].

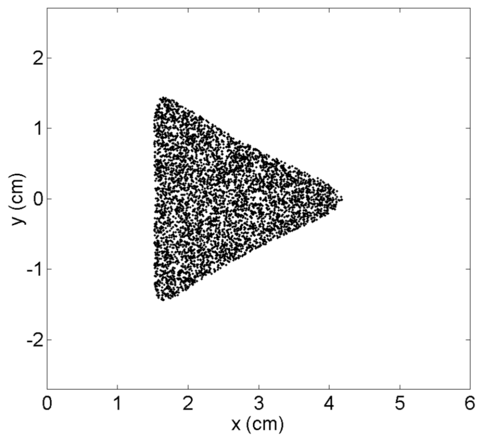

Figure 3 Configuration space image of beam emerging from kicker experiencing a large sextupole field

Despite the strong deformation of the beam image the emittance growth is predicted to be about 53% for this beam. However, transport calculations have also shown that it is possible to transport a smaller radius high current beam ~2 kA through the kicker giving an estimated emittance growth on the order of 2%.

5 MAGNETIC DIPOLE SEPTUM

The septum magnet provides an additional angular kick to the beam as it emerges from the kicker. The kick is in opposite directions on either side of *x=0*. The septum is shown schematically in Figure 4.

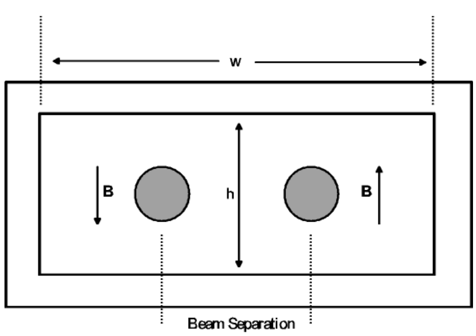

Figure 4 Magnetic dipole septum magnet

The dipole magnetic field required to produce a beam exit angle of ~15° is determined from

$$B\ell = \frac{mc}{e}\sqrt{\left(\frac{E_b}{mc^2}\right)^2 + 2\left(\frac{E_b}{mc^2}\right)} \times \left[\sin\left(\theta_i + \Delta\theta\right) - \sin\left(\theta_i\right)\right] \tag{7}$$

where ℓ is the axial length of the magnet, θ_i is the incident beam angle, $\theta_i + \Delta\theta$ is the desired exit beam angle, and E_b is the beam energy. A preliminary design for a dipole septum magnet to be used with the ETA-II kicker is being developed. The parameters for the design are an axial length of 20 cm, and a magnetic field of about 276 Gauss for a beam energy of 6.3 MeV. The dimensions of the aperture are about h=6 cm high and w=31 cm wide. Careful optimization of the design is required to minimize possible emittance growth in the transition region where the field changes sign. Currently, magnetic modules are being developed for particle transport codes to estimate the emittance growth through the septum magnet. With careful design including shims preliminary estimates show an emittance growth on the order of 4% through the septum magnet.

6 CONCLUSIONS

Self-consistent models are being developed for modeling the transport of high current space-charge dominated beams through fast beam kickers and dipole septum magnets. The effect of beam-induced forces due to the wakefields of the beam are included in the analysis. In addition, emittance growth due to nonlinear forces associated with higher order multipoles in both the kicker and septum have been estimated. Preliminary estimates of beam-induced steering are consistent with the experimental program [4]. The effect of space-charge, image forces, and fringe fields in the structures have yet to be included.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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