THE EFFECTS OF RF ASYMMETRIES ON PHOTOINJECTOR BEAM QUALITY *

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Abstract

A general multipole-based formalism to study the effects of RF asymmetries on the production of ultra-high brightness beam is presented, which employs both analytical and computational techniques. These field asymmetries can cause the degradation of beam emittance due to time dependent and nonlinear focusing effects. Two cases of interest are examined: the dipole asymmetry produced by a coupling slot in a standard high gradient rf gun, and the higher multipole content introduced by the support/cooling rods in a PWT structure. Practical implications of our results, as well as comparison to cold test and beam-based experimental tests, are discussed.

1 RF FORCE-DERIVED EMITTANCE

In a high gradient rf photoinjector, the necessity of using violent longitudinal acceleration also implies the existence of large transverse forces. These forces are time-dependent, and may be nonlinear or non-axisymmetric as well. All of these attributes can give rise to transverse emittance growth. Time dependent monopole[1] and dipole[2] fields can cause correlations between the beam's transverse and longitudinal phase spaces, which, while not contributing to the so-called slice emittance (the transverse emittance of a narrow longitudinal slice of the beam), can increase the total projected transverse emittance. We shall discuss the relationship between these emittance contributions and the Panofsky-Wenzel theorem, as well as observations verifying the conclusions we reach from this analysis.

Nonlinear fields have typically been considered in the context of the axisymmetric, non-synchronous spatial harmonics of the rf field. In this paper, we examine the contribution to synchronous rf multipole fields to the emittance, and analytically estimate the amplitude of these multipoles for rf structure types of interest. We compare the analytical estimates with experimental evidence and computer simulations.

2 PANOFSKY-WENZEL THEOREM

As cavities are designed first and foremost to accelerate, it is of interest to relate the longitudinal acceleration which is imparted to a given particle. This is accomplished by an updated version of the Panofsky-Wenzel theorem[3], in which we take into account the fact that the electrons which are accelerated from rest starting from a point (a photocathode) where the field is not zero. The Panofsky-Wenzel theorem explicitly assumes in its derivation that the particle experiencing Lorentz forces in the rf cavity environment moves parallel to the axis at constant velocity. The approximation of constant velocity is as badly violated as can be close to the photocathode, but in this region there are few transverse forces. Thus the application of the theorem is still reasonable in this case.

Our version of the Panofsky-Wenzel theorem gives the integrated transverse and longitudinal momentum "kicks" in terms of the components of the rf vector potential $\vec{A}$

$$\Delta\vec{p}_\perp = \frac{q}{c}\left[\int_{z_i}^{z_f}\frac{\partial\vec{A}_\perp}{\partial\zeta}dz + \int_{z_i}^{z_f}\vec{\nabla}_\perp A_z dz\right], \text{ and} \quad (1)$$

$$\Delta p_z = \frac{q}{c}\left[\int_{z_i}^{z_f}\frac{\partial A_z}{\partial\zeta}dz\right], \text{ with } \zeta = z - ct. \quad (2)$$

The first term in Eq. 1 vanishes because it is a perfect differential, and the transverse components of the vector potential vanish at the cathode, and outside of the cavity. Thus we have the relation

$$\frac{\partial(\Delta p_\perp)}{\partial\zeta} = \vec{\nabla}_\perp(\Delta p_z). \quad (3)$$

We consider a multipole standing wave field with a sinusoidal dependence of the phase on distance away from the power coupler,

$$E_z = E_0\sin\left(\omega t - \kappa_y y + \theta_0\right)\cos(kz)\sum_{n=0}^{\infty}a_n r^n\cos(n\phi) \quad (4)$$

The asymmetry term inside of the sine function is the phase asymmetry due to power flow (finite Q effect), and the series expansion is the multipole content of the mode fields. The vector potential associated with Eq. 4 is

$$A_z = \frac{E_0}{k}\cos\left(\omega t - \kappa_y y + \theta_0\right)\cos(kz)\sum_{n=0}^{\infty}a_n r^n\cos(n\phi). \quad (5)$$

3 POWER FLOW EFFECTS

To isolate the transient power flow component of the acceleration, we use only the lowest multipole component field, to arrrive at longitudinal momentum gain in a gun of length L_g of approximately

$$\Delta p_z = \frac{eE_0 L_g}{2c}\cos\left(k\zeta - \kappa_y y\right)$$
$$\cong \frac{eE_0 L_g}{2c}\left[1 - \frac{(\Delta\phi)^2}{2} - \frac{\left(\kappa_y y\right)^2}{2}\right],\ \Delta\phi = k\Delta\zeta. \qquad (6)$$

The transient power flow wave number can be estimated as $\kappa_y \cong k/Q$, where Q is the unloaded quality factor, which is of order 10^4. Thus for reasonable beam size parameters, the effect of the power flow can be neglected.

4 MULTIPOLE FIELDS

4.1 Monopole effects

For the monopole component of the field, with normalization $a_0 = 1$, the acceleration is independent of transverse offset (*e.g.* y), and the transverse emittance growth for a beam with a uniform density distribution propagating near the peak acceleration phase is

$$\varepsilon_{ny} = \bar{\gamma}\sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2}$$
$$= \sqrt{\tfrac{13}{20}}\,\frac{eE_0}{2m_e c^2}\sigma_y^2\left(k\sigma_z\right)^2. \qquad (7)$$

This is the rf emittance contribution first analyzed by Kim[1], and can be mitigated by keeping the beam sizes small.

4.2 Dipole effects

The lowest significant order asymmetry has traditionally arisen from the existence of a coupling slot on one side (in y)of the cavity. In the first 1.5 cell BNL designed S-band gun, the coupling was in both cells, and thus initial condition on the transverse vector potential is $A_y = 0$, giving a transverse momentum kick of

$$\Delta p_y = \partial_y \int \Delta p_z d\zeta = \frac{eE_0}{2c}\frac{a_1}{k}L_g \sin\left(k\zeta\right)$$
$$\cong \frac{eE_0}{2c}a_1 L_g \zeta \qquad (8)$$

This phase dependent dipole kick gives rise to an effective projected emittance

$$\varepsilon_{n,y} = \frac{eE_0}{2m_e c^2}a_1 L_g \sigma_y \sigma_z. \qquad (9)$$

According to the Panofsky-Wenzel theorem, the transverse momentum kick is accompanied by an acceleration which is dependent on the offset of the electron in y,

$$p_z(y)c \cong eE_0 L_g\left(1 + a_1 y/k\right). \qquad (10)$$

If one measures this asymmetry, then one can determine a_1, and the expected emittance growth due to dipole kicks can be estimated. This was done on a 1.5 cell gun obtained from BNL at UCLA[4], with a view of the momentum spectrometer shown in Fig. 1. Here the particles at larger y (actually at large x in the gun, as the focusing solenoid provides a nearly 90 degree rotation) are seen to have a smaller momentum in the spectrometer.

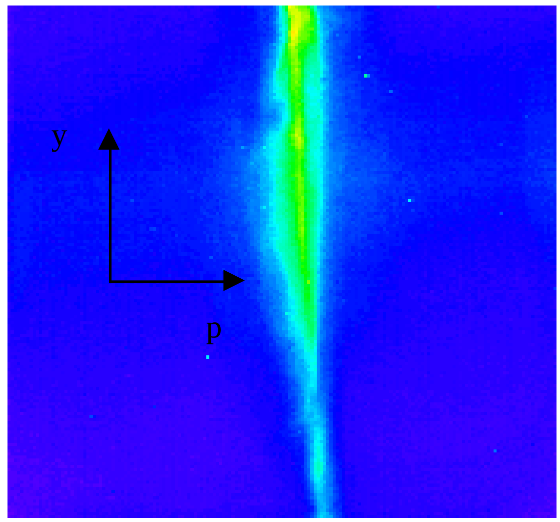

Figure 1. Electron beam (green) image in focal plane of spectrometer, with smaller energy electrons at larger *y*.

From this image, and knowledge of the bunch size and length, it was deduced that the gun dipole asymmetry contributed 3.5 mm-mrad to the normalized rms emittance. The low charge vertical emittance in this gun was measured to be 5 mm-mrad, most of which came not from the more familiar monopole effects, but from rf dipole components. This is partially due to the overcoupling of the device ($\beta = 1.6$); the coupling slots were anomalously large, and the dipole component of the rf field was larger than necessary.l

4.3 Higher multipole effects.

In the next-generation rf guns[Palmer,Colby] beyond the 1.5 cell BNL style model, several design innovations were implemented, including the coupling of external power only through the full cell, and the use of a dummy slot opposite to the coupling slot for dipole symmetrization. These schemes worked well, and have additionally been supplemented by the use of a race-track outer wall geometry[5] to eliminate the quadrupole components of the field left after dipole symmetrization.

In the new PWT photoinjector structure, under development by a UCLA/DULY Research collaboration, the structure is based on disks which are not connected to the outer wall, but are supported by four rods (the cross-sections of two are shown in Fig. 2). The cell-to cell coupling in this device is obtained through the annular region between the disks and the outer wall, and can be very strong, leading to excellent mode separation. The external coupling is through the outer wall, and is so far from the axis that it does not give rise to significant dipole components of the field. In fact, the rods, which are relatively close the axis, give rise to a dominant octupole field perturbation.

We have examined this perturbation both analytically and through field simulations. The rods effect lasts for the entire structure, just as the dipole component, and so the normalized emittance in such a long device may be impacted more severely than in a short gun. All of the higher multipole components which have a strong effect on the beam will have a speed-of-light phase velocity, and thus have a transverse field profile which obeys the equation $\nabla_{\perp}^{2}E_z = 0$ with solutions as in Eq. 4. The boundary conditions for the situation with the rods may be approximated as the field being constant at the rod offset radius ρ, but dropping to zero in the region of the rods (which have radius *b*). Fourier analysis of this rectangular profile in ϕ gives the ratio of the octupole to monopole components of the field,

$$\frac{a_4}{a_0} \cong \frac{2\sin(4b/\rho)}{\rho^4\left((4b/\rho)-\pi\right)} \qquad (11)$$

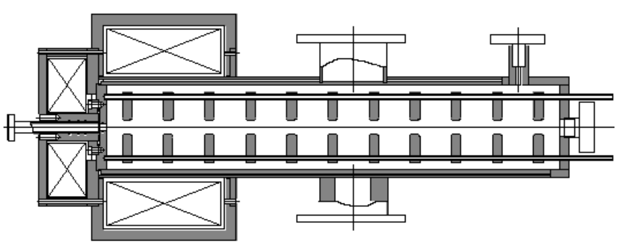

Figure 2. S-band PWT photoinjector cross-section, with 2 support/cooling rods showing.

For the S-band PWT linac, Eq. 11 gives $a_4/a_0 \cong 10^{-3}$ cm^{-4}, while the GdfidL 3-D field simulations shown in Fig. 3 give $a_4/a_0 \cong 1.3\times10^{-3}$ cm^{-4}, which is good agreement for so rough of a model.

The effect of the octupole component on the emittance in this device can be estimated as

$$\varepsilon_{n,y} = \frac{\sqrt{3}}{14}\gamma_f a_4 \sigma_y^4 \sigma_z, \qquad (12)$$

where we have written it as proportional to the final energy $\gamma_f m_e c^2$ to emphasize that the emittance is linearly dependent on the length of the structure. For the 20 MeV S-band PWT photoinjector at UCLA, $\sigma_z = 0.7$ mm, $\sigma_y \cong 1.5$ mm, and the expected octupole contribution to the emittance is $\varepsilon_{n,y} \cong 2.3\times10^{-8}$ m-rad, which is almost two orders of magnitude smaller than the expected emittance due to monopole rf and space-charge effects.

On the other hand, for the proposed X-band PWT photoinjector[6] under study by a DULY/UCLA/LLNL collaboration, the rods must expand by a factor of 50% relative to the disk size in order to provide adequate cooling water flow. In this case Eq. 11 gives $a_4/a_0 \cong 0.15$ cm^{-4}, while the beam, for 1 nC operation (as in S-band), is smaller by a factor of $\sqrt{3}$ in all dimensions. In this case, the expected octupole contribution to the normalized emittance is $\varepsilon_{n,y} \cong 2.1\times10^{-7}$ m-rad. This is now significant, as it is roughly 20% of the design monopole emittance. In addition, it implies that it would be unwise to raise the charge Q significantly in this device, as this would result octupole-induced emittance scaling[8] as $Q^{5/3}$.

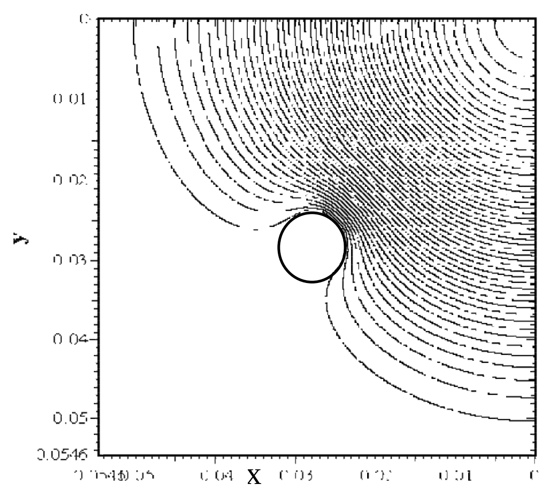

Figure 3. Calculated contours of constant E_z in S-band PWT at mid-cell, from GdfidL simulation.

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