MODELING SKEW QUADRUPLE EFFECTS ON THE UMER BEAM*

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Abstract

This is a numerical and experimental study of the effects of skew quadrupoles on the beam used in University of Maryland Electron Ring (UMER). As this beam is space-charge dominated, we expect new phenomena to be present compared to the emittance-dominated case. In our studies we find that skew quadrupoles can severely affect the halo of the beam and cause emittance growth, even in the first turn of the beam. For our simulations we use the WARP particle-in-cell code and we compare the results with the experimental study of skew quadrupole effects.

INTRODUCTION

The University of Maryland Electron Ring (UMER) [1] is a low cost experimental facility used to model space-charge dominated beams. Such types of beams are of interest for current, planned and future accelerators, such as free electron lasers [2], spallation neutron sources [3] or heavy ion fusion [4]. Two separate but closely related phenomena encountered during the transport of intense beams are emittance growth and the creation of halos [5]. Both of those phenomena can deteriorate beam quality. In particular, emittance measures the compactness of the beam in phase space and for this reason it has been called a "figure of merit" for beam quality. On the other hand, halo creation can increase the emittance of the beam, lead to uncontrolled beam losses and (in the case of high energy particles) nuclear activation of the pipe wall, making maintenance of the facility harder. Skew quadrupoles have been studied before in the context of intense beams. These studies have associated skew quadrupoles with rotational modes of the beam [6, 7], emittance exchange between the x and y planes [8] and the creation of halo [9]. In the current paper, we follow up on the work of Li et al [10] by incorporating more realistic initial beam distributions and comparing simulations with experimental results from UMER.

SIMULATION SETUP

The code used in all the simulations is WARP, a particle-in-cell (PIC) code that has been tested extensively and is ideally suited for simulations of space charge dominated beams. For our simulations we use a number of initial particle distributions, namely:

1. Kapchinsky - Vladimirsky (K-V) which is an ellipsoid in 4-dimensional phase space with uniform projections on $x-y$ and $x'-y'$ planes.
2. semi-Gaussian (S-G) which has a uniform projection in $x-y$ plane and a Gaussian one in $x'-y'$.
3. More realistic distributions generated from self-consistent gun simulations (e-gun) [11].

In the latter case, the beam distribution coming out of the gun already has a halo. The halo is attributed to particles emitted from the edge of the cathode, who then go on to cross the center of the beam before reaching the anode. The particles following these complex orbits eventually contribute to the halo seen in simulations downstream. The primary focus of our simulations and experiments is a beam with pulse length 100 ns and current 18.5 mA. For an undepressed phase advance of 76 degrees (the normal operating point of UMER) this leads to an intensity paramater χ of 0.85, making the beam space charge dominated [1]. This beam is created in UMER by applying a circular aperture with 1.5 mm radius right before the injection section, thus lowering the current to 18.5 mA from 112 mA. An equivalent procedure is used in the code to create the lower current beam from the full beam coming out of the gun. The magnet lattice, both in the injection section and the ring, is modelled using hard edged magnets, which can have quadrupole fields of arbitrary skew angle. We can define the skewness of the beam in terms of distribution moments using the formula:

$$\alpha = \frac{1}{2}\arctan\left(\frac{2\Delta xy}{\Delta x^2 - \Delta y^2}\right) \quad (1)$$

The operator Δ is defined as in [7], namely $\Delta ab = \langle ab\rangle - \langle a\rangle\langle b\rangle$, where $\langle\rangle$ indicates averaging over all the particles.

EXPERIMENTAL SETUP

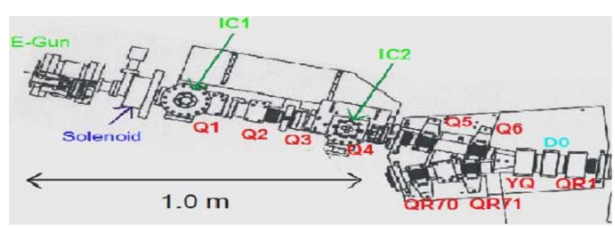

Figure 1: Schematic of the injection section of UMER. The skew quadrupole is located in Q6.

Skew quadrupole experiments have been performed on UMER before [10]. In those studies, the skew quadrupoles

[1] χ is defined in [5] and is essentially the ratio of space charge forces to external focusing. Thus, a beam is called space charge dominated if χ is larger than 0.5 and emittance dominated if it is smaller than 0.5

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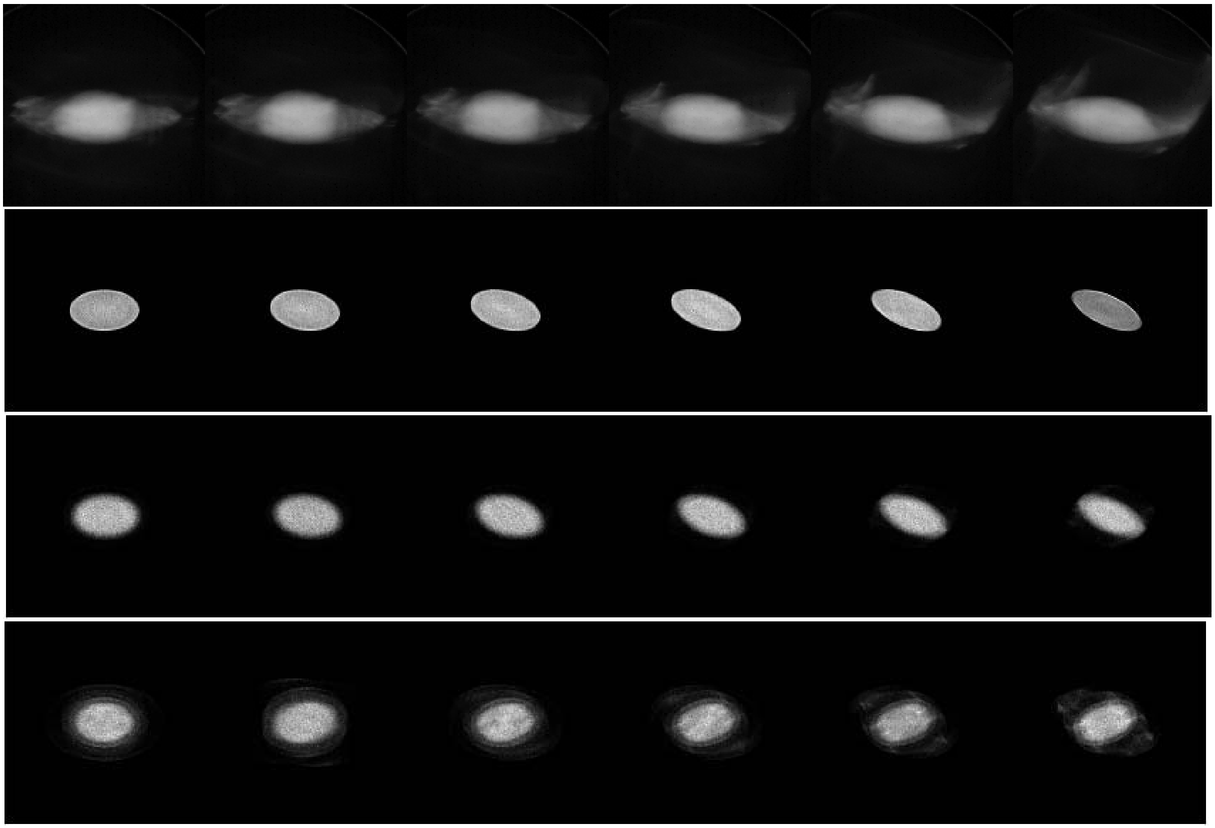

Figure 2: Comparison of experiment (first line) and simulation (K-V, semi-gaussian and e-gun initial distributions respectively.)

were constructed from printed circuit (PC) quadrupoles. In our experiments, we used the same technique, namely mounting 2 PC quadrupole magnets on the same mount and at an angle of 45 degrees with each other. We can adjust the skew component of the quadrupole field by adjusting the ratio of the currents running through each circuit, assuming the two PC magnets are identical. Indeed, the skew angle θ of the quadrupole field is given from Eq. 2:

$$\theta = \frac{1}{2}\arctan\left(\frac{I_s}{I_0}\right) \tag{2}$$

where I_s and I_0 are the currents through the skew and normal PC components respectively and θ is small. We can measure experimentally the skew angle of the distribution by analyzing pictures of the beam, measuring the necessary moments and using Eq. 1. In our setup, the skew quadrupole was mounted on the last quadrupole mount of the injection section, so the beam enters the ring having a rotation in the $x - y$ plane (Fig. 1).

RESULTS

We show both experimental and numerical data, comparing 3 different simulations (K-V, S-G and e-gun) with experiment at a diagnostic chamber inside the ring (RC3, roughly 3.1 meters from the electron gun).

In Fig. 2 we show pictures of the beam inside the ring from experiment (first row) and simulations (rows 2-4) for 6 different initial skew angles. It is obvious that the UMER beam and the e-gun simulation already have a substantial halo, independent of the skew angle of the quadrupole at Q6. In Fig. 3 we compare the rotation angles measured in the experiment and in simulation as a function of initial skew angle.

The disparity between the numerical and experimental results is evidently related to the existence of halo in the UMER beam. In particular, we see that the halo particles behave differently from the core of the beam, and this can greatly influence the rotation of the core as well. Since halo particles are (by definition) far from the beam centroid, they have a disproportionate effect on the various moments used to calculate beam rotation in Eq. 1. This is also illustrated by the fact that both the K-V and S-G cases have small halos and behave similarly to each other, but differ significantly from both the experiment and the e-gun case. On the other hand, the e-gun case does not agree with the experiment either, since the detailed structures in the halo differ in the two cases In Fig. 4, the emittances from the 3 simulations are compared, again at RC3.

The emittance of the K-V beam remains roughly constant as we increase the skewness of the beam, reflecting the fact that in this case the beam has a hard edge which

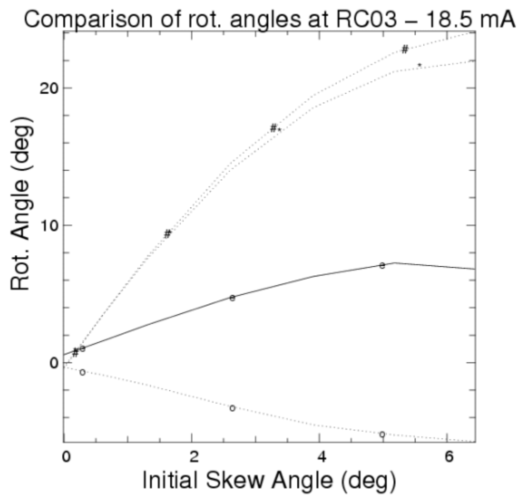

Figure 3: Comparison of skew angles between experiment and simulation as a function of initial skew angle.*:S-G, #:K-V, o:e-gun, e:experimental.

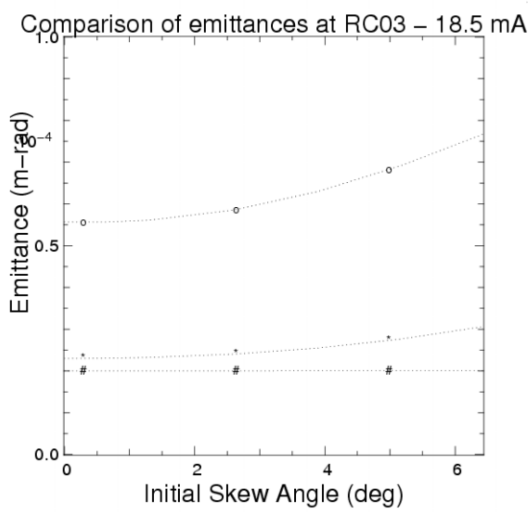

Figure 4: Comparison of emittances as a function of initial skew angle.*:S-G, #:K-V, o:e-gun.

persists. On the other hand, both the S-G and the e-gun beams have halos, e-gun to a much bigger degree than S-G. This shows up as both greater emittance and as emittance growth as the halo is increased by increasing the initial skew.

CONCLUSION

In this paper, we have demonstrated that skew quadrupoles can cause halo formation and emittance growth in space charge dominated beams. On top of that, the UMER beam has a halo independently of skew quadrupoles and simulations by I. Haber have indicated that this can be attributed in part to the detailed structure of the initial beam distribution. One of the difficulties faced in modeling skew quadrupoles is the fact that halos have a disproportionately big effect on value of the beam's rotation angle. This implies that in order to accurately simulate the effects rotations we need detailed knowledge of the halo and its causes.

ACKNOWLEDGMENTS

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