PEPPER-POT BASED DIAGNOSTICS FOR THE MEASUREMENT OF THE 4D TRANSVERSE PHASE SPACE DISTRIBUTION FROM AN RF PHOTOINJECTOR AT THE AWA*

J.G. Power#, M. E. Conde, W. Gai, W. Liu, ANL, Argonne, IL 60439, U.S.A.
P. Piot, NIU, DeKalb, IL, 60115, U.S.A.

Abstract

Phase space measurements of RF photoinjectors have usually been done with multislit masks or scanning slits. These systems implicitly ignore the correlations between the X and Y planes and thus yield measurements of the projected 2D phase space distributions. In contrast, a grid-patterned pepper-pot is capable of measuring the full 4D transverse phase space distribution, f(x,x',y,y'). 4D measurements allow precise tuning of electron beams with large canonical angular momentum, important for electron cooling and flat beam transformation, as well as zeroing the magnetic field on the photocathode for ultra low emittance applications (e.g. SASE FEL, ERL FEL). In this talk, we report on the development of a pepper pot diagnostic to measure the 4D transverse phase space of the 1 nC electron beam from the Argonne Wakefield Accelerator (AWA) RF photoinjector. The diagnostic is simulated with TStep, including the passage of the electron beam trough the mask and tracking of the beamlets to the imaging screen.

INTRODUCTION

High demand is being placed on electron beam sources for a variety of future applications including energy recovery linacs, advanced acceleration methods, and SASE FEL's, just to name a few. Approaches to high-brightness electron sources has become more diversified in recent years branching out from the workhorse RF photocathode gun to now include RF guns with small diameter thermionic cathodes [1] and HV pulsed electron guns with thermionic cathodes [2]. Improvement of the source beam quality requires a thorough understanding of the high-brightness e-beam dynamics in order to control such phase-space diluting effects like space-charge, wakefields, etc. Such understanding can be increased by detailed measurement of the transverse phase space. In addition to high-brightness sources, some applications require precise control of the electron beam canonical angular momentum.

Ideally, one wants to measure the 4D transverse phase space distribution complete with X-Y coupling, but most traditional diagnostics fail in this regard. For example, quad scans, 3-screen measurements, and OTR-based methods only yield the rms emittance while scanning slits average over many shots and thus smooth out details. Even advanced methods such as phase space tomography have limitations since it allows the beam to drift to a screen thus implicitly ignoring the complicated evolution of the phase space in the drift as seen in the emittance compensation process.

In this paper, we discuss an effort recently started to use a pepper pot (PP) with a 2x2 grid of holes to both accurately measure the 2D transverse phase space and to eventually measure the complete 4D phase space including x-y correlations.

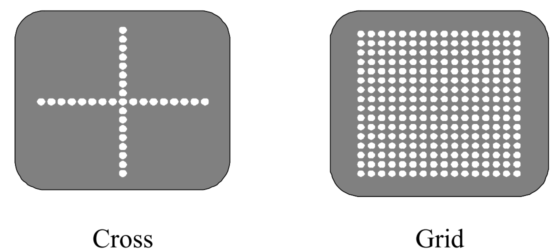

Figure 1: Traditional Pepper Pot Designs.

IMPROVED 2D MEASUREMENTS WITH A GRID-BASED PEPPER POT

A traditional PP design [3] called *the cross* has a horizontal and vertical array of holes arranged in the pattern of a cross drilled through a dense plate (Fig. 1). While most of the beam is blocked by the plate a number of beamlets pass through the holes to a downstream imaging screen. The emittance can be retrieved [4] from the pattern of beamlets on the imaging screen. An alternate design, *the grid*, has a 2x2 matrix of holes arranged in the dense plate. In the remainder of this section we compare the cross to the grid for the accurate retrieval of the 2D emittance.

Comparison of the PP cross to the PP grid was done by simulating the propagation of a 1 nC photoelectron beam from the AWA RF gun, through the PP, and tracking the beamlets to a normal incidence profile screen Y (Fig. 2).

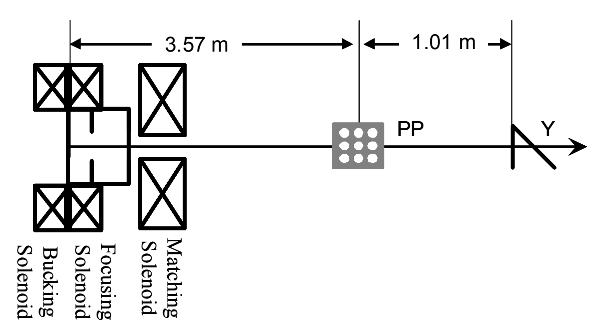

Figure 2: Simplified Schematic of the AWA beamline.

* The work is supported by the U.S. Department of Energy under Contract No. DE-AC02-06CH11357 with Argonne National Laboratory.
#jp@anl.gov

Simulations were done with the 3D space charge code TStep to track 5 million macroparticles from the photocathode to the PP, a mask was applied with the *PepperPot* element in TStep, and then a greatly reduced number of macroparticles (~100 thousand) in the beamlets were tracked to Y (Fig. 2). Both the PP cross and the PP grid had hole diameter of 100 μm and hole spacing of 1 mm. The beam parameters for the two cases that were studied are given in Table 1.

Table 1: Case Studies Comparing the Cross and Grid

Parameter (unit)	Case I	Case II
bunch charge (nC)	1.0	1.0
Gaussian laser rms duration (ps)	4.0	3.4
top-hat laser rms radius (mm)	0.33	1.0
laser injection phase (deg)	43.297	50
E-field on cathode (MV/m)	77	70.6
Bucking peak axial B-field (T)	0.1206	0.0995
Focusing peak axial B-field (T)	0.1206	0.0995
Matching peak axial B-field (T)	0.4942	0.4284
Kinetic Energy (MeV)	8.08	7.40
emittance before PP (μm)	1.47	5.03
emittance after Cross (μm)	1.40	3.48
emittance after Grid (μm)	1.46	4.92

The transverse beam parameters along the beamline are shown in Figure 3 for both cases. In Case I, the minimum emittance occurs at the location of the PP and the spot size is small relative to the hole spacing. From the simulations, the emittance before the PP is 1.47 μm and the emittance transmitted by the PP cross is 1.40 μm (line labelled 'cross' in Fig. 3) while that transmitted by the PP grid is 1.46 μm (line labelled 'grid in Fig. 3). In other words, the PP cross underestimates the emittance by approximately 5% while the PP grid is within 1%. Although the cross is less accurate than the grid, in this case, both results are accurate relative to the experimental resolution. In Case II, the minimum emittance occurs slightly before the PP. From the simulations, the emittance before the PP is 5.03 μm and the emittance transmitted by the cross is 3.48 μm while that transmitted by the grid is 4.92 μm. In other words, the PP cross underestimates the emittance by approximately 30% while the PP grid is about 2% low. It seen that for Case II, the PP cross significantly underestimates the actual emittance of the beam.

To understand why the cross is less accurate for Case II than Case I, we plot the beamlet distributions at screen Y in Figure 4. From the figure, it is apparent that the spot size is small relative to the hole spacing in Case I since

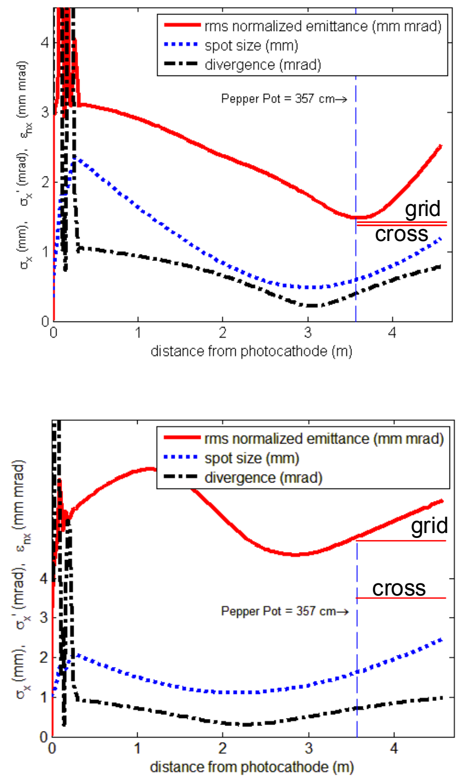

Figure 3: Transverse beam parameters for Case I (top) and Case II (bottom).

only a few beamlets pass through the plate. In Case II, however, we see that the beam spot size is large compared to the hole spacing, as evidenced by the larger number of beamlets transmitted.

Based on similar reasoning and Figure 4, we can understand why the cross is less accurate than the grid. The PP cross inaccurately measures the emittance because it undersamples the phase space. In addition, since high-brightness photoelectron beams have very bright cores, the PP cross preferentially samples the core of the beam thus producing an artificially low value for the emittance.

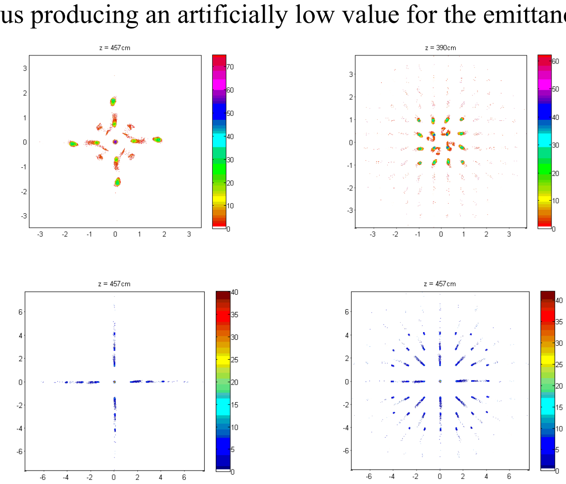

Figure 4: Beamlets transmitted by the cross and grid for Case I (top) and Case II (bottom).

ELIMINATING THE X-Y COUPLING

Production of a low-emittance, round electron beam requires that the longitudinal magnetic field on the cathode (B_{z0}) be zero; this is the purpose of the *Bucking Solenoid* (Fig. 1). Due to the conservation of canonical angular momentum and Busch's Theorem, a non-zero B_{z0} introduces a coupling between the x and y-planes which in turn gives rise to magnetic emittance term thus increasing the overall emittance of the beam. In practice, it can be difficult to know if B_{z0} is zeroed on the cathode.

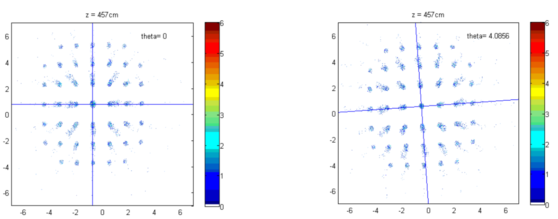

Figure 5: The Grid pattern is upright at 0^0 for B_{z0}=0 (left) and rotated to 4^0 for B_{z0}=100 Gauss (right).

TStep simulations were performed to study the effect of the orientation of the PP beamlets as a function of B_{z0}. Two primary results were found in the simulations. (i) The overall emittance increases with the B_{z0}. Based on Bucsh's Theorem one can show that contribution of the magnetic emittance term scales as $R^2 * B_{z0}$, which is consistent with the TStep simulations. (ii) The rotation of the beamlet pattern scales with B_{z0}. When B_{z0} = 0 (Fig. 5, left) the orientation of the pattern of beamlets transmitted by the PP grid is parallel to the machine orientation. However, when B_{z0} is not equal to zero, the beamlet orientation will be rotated with respect to the machine orientation. For the beam parameters listed in Case II and for B_{z0}=100 Gauss (Fig. 5, right) the pattern is rotated approximately 4^0.

The PP grid therefore offers an easy way for the experimentalist to insure that B_{z0} = 0. One approach to zeroing B_{z0} is to sweep at each value of the *focusing* and *matching solenoid* but this is labor intensive. However, based on the simulations described above, the experimentalist can simply scan the focusing solenoid until the pattern orientation is upright.

4D EMITTANCE

Due to the complicated nature of the phase space near the electron source, measurement of the complete 4D phase space is superior to the measurement of the 2D projected phase space. The grid patterned PP is naturally suited for this task. However, it is surprising to find out that the 4D phase space is transmitted by both the PP cross and PP grid. This can be seen as follows. First, recall that the 4D sigma matrix is given by,

$$\Sigma_{4D} = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle y^2 \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'^2 \rangle \end{pmatrix} \quad (1)$$

TStep simulations were run through both the PP cross and PP grid and then the 4D sigma matrix was calculated. The result for the case corresponding to Figure 5 (right) yields for the PP grid,

6.3644	2.0414	-0.0178	-0.2239
2.0414	0.6783	0.2198	0.0010
-0.0178	0.2198	6.5650	2.1225
-0.2239	0.0010	2.1225	0.7105

while the result for the PP cross is,

4.1611	1.3835	0.0447	-0.1354
1.3835	0.4772	0.1896	0.0152
0.0447	0.1896	4.5314	1.5568
-0.1354	0.0152	1.5568	0.5522

Inspection of the matrices shows that both PP's transmit the off-diagonal, 2x2, sub-matrices, representative of coupling, but that the PP cross underestimates the true emittance.

FUTURE WORK

The next step will be to benchmark the 2D emittance recovery algorithm previously developed [3] to TStep simulations. We then plan to extend the 2D emittance recovery formalism [4] to 4D and then measure the 4D emittance of the AWA RF photoinjector.

CONCLUSION

Detailed simulations have been performed to study the accuracy of two traditional pepper pot (PP) patterns, the grid and the cross. Simulations revealed that the PP grid yields accurate 2D measurements but that the cross PP undersamples the beam and can produce inaccurate emittance measurements. It was also shown that the orientation of the beamlet pattern after the PP grid provides a convenient way to eliminate the X-Y coupling arising from a non-zero longitudinal magnetic field on the cathode. Lastly, simulations reveal that both the PP cross and PP grid are capable of measuring the 4D emittance, but that the PP cross once again under estimates the true emittance of the beam.

REFERENCES

[1] P.N. Ostroumov et al., Proceedings of LINAC08

[2] K. Togawa et al., Phys. Rev. ST Accel. Beams 10, 020703 (2007)

[3] J.G. Power et al., Proceedings of PAC07

[4] M. Zhang, "Emittance Formula for Slits and Pepper-. pot Measurement", FERMILAB-TM-1998