Measurement of Electric Field Uniformity in an Electrostatic Separator

Weiran Lou and James J. Welch, *Cornell University, Ithaca NY* *

Introduction

Electrostatic separators are used in several modern storage rings to generate large distortions of the closed orbit as a means of avoiding undesirable beam-beam collisions in the arcs. Unlike comparable magnetic elements, there is not a well developed technology to measure the electric field quality of electrostatic separators, so the ultimate field uniformity is largely left up to the conservatism and skill of the designers and fabricators of the devices. Measurements of the electric field integrate over the entire path of the particles, including end effects, and sense the effects of misalignments, warpage and other mechanical errors on individual units. This ability not only helps with quality control, but also to interpret machine studies where the results are sensitive to the nonuniformities of the electric field. In particular, electric field measurements can provide a better estimate of the tuneshift and sextupole moments as a function of beam position in the separators.

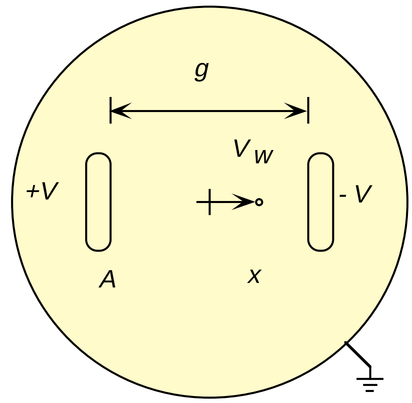

Figure 1: The measurement wire, electrodes, chamber and the voltages are shown schematically in this figure.

Description of Method

The basic technique we used for measuring the electric field is to stretch a long thin wire along a hypothetical particle trajectory between the electrodes and adjust the potential of the wire relative to the electrode potentials to zero out the net charge on the wire. The induced charge is observed by oscillating the electrode voltages so that the resulting induced currents can be seen on an oscilloscope. Once the wire potential is determined the wire can be translated a precise amount and the process repeated. The electric field is obtained by taking the derivative of the wire potential data with respect to the position of the wire. In practice the highest accuracy is obtained by first setting of the voltage divider which sets the potential of the wire relative to the electrodes, and then adjusting the position of the wire to zero out the induced signal.

One nice features of this method is that it uses a motionless wire; the field is oscillated to produce the signal. (An alternate arrangement is described in [1].) Also, the required equipment is quite modest: a potentiometer, a sinusoidal single source (eg. Wavetek), an ordinary transformer, two translation stages, an oscilloscope and wire, were all that we used. The overall accuracy depends mostly on the quality of the potentiometer.

To understand how this works, first imagine that the charge on the electrodes is unperturbed by the presence of charge on the wire, (See figure 1). The effect of the perturbation is negligibly small over the range of wire positions of interest because the induced net charge on the wire can be made essentially zero compared with the charge on the electrodes. We will call E_0 the electric field generated by the charge on the electrodes only. It is this electric field that we wish to measure.

Similarly imagine that the field generated by the charge on the wire is approximately the simple line charge field in free space (no electrodes or chamber) which in cgs units is

$$E_w(r) = \frac{2\lambda}{r}$$

where λ is the net charge per unit length on the wire and r is the distance from the wire center. The potential of the wire is maintained externally and determines the charge on the wire at each wire position. Clearly this latter approximation is not valid near the electrodes. Whatever the actual wire field is, we only require that it go to zero when the net charge on the wire is zero. This will not be true very close to the wire where polarization charges create a dipole field which cancel out the electrode field inside the wire. But the dipole field have very short range and will not affect the charge distribution on the electrodes and therefore do not change E_0. Similarly it will not be true near the electrodes where image charges are induced, unless $\lambda = 0$.

Analysis

First we put $\pm V$ on the two electrodes and hold the wire at V_w. The wire is at position x. We will define the origin of the coordinate system such that for a wire at the origin there is no net

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charge on the wire ($\lambda = 0$) when the wire is held at ground potential ($V_w = 0$). Normally, for a symmetric separator this would be exactly between the two electrodes, but due to imperfections could be different in practice.

$E = E_0 + E_w$ is the total electric field at any point, and A is the x coordinate of V electrode (approximately $-g/2$). Then

$$
\begin{aligned}
(V - V_w) &= \int_A^x E dl && (1)\\
&= \int_A^0 E_0 dl + \int_0^x E_0 dl + \int_A^x E_w dl && (2)\\
&\approx \int_A^0 E_0 dl + \int_0^x E_0 dl + \int_{A-x}^{-\phi/2} \frac{2\lambda}{l} dl && (3)
\end{aligned}
$$

From the definition of the origin we have

$$V = \int_A^0 E_0 \cdot dl \qquad (4)$$

With this definition applied back to equation 3 we have

$$-V_w \approx \int_0^x E_0 dl + \int_{A-x}^{-\phi/2} \frac{2\lambda}{l} dl \qquad (5)$$

Equation 5 can be used in the following manner. For each wire position adjust V_w to make $\lambda \approx 0$, record the wire position and voltage. Since $\lambda \approx 0$

$$V_w = -\int_0^x E_0 dl \qquad (6)$$

so the electric field may be obtained from $E_0(x, y) = -\nabla V_w$.

Measurements

A prediction for the shape of the electric field in the gap was obtained from a 2D successive over-relaxation code written specifically for this separator. In the design of the electrodes considerable effort was expended to optimize the field quality by minimizing the nonuniformity of the electric field at the origin and nearby. If the uniformity of the field in the real separator was similar to the design there should be almost no observable beam dynamical effects due to the separator field.

A prototype for the new low impedance horizontal separators was measured. The electrode length is 2.5 m and the gap between the electrodes is about 10 cm.

Figure 2 shows the measured V_w/V versus the horizontal coordinate. Superposed on this is the calculated electric potential due 2D code. Clearly there are easily measurable deviations.

Figure 3 shows the deviation of a fourth order fit to the measured data from the calculated field. The linear and nonlinear field coefficients are tabulated in table 1.

It was found that the calculated kick at the origin agrees well the measured kick, (see the $b1$ terms in table 1). However, the nonlinear fields of the prototype were much larger than those predicted for perfect 2D geometry. The discrepancy is easily seen in figure 2, but is more obvious in figure 3 where the theory is subtracted from the measured values. The theoretical voltage

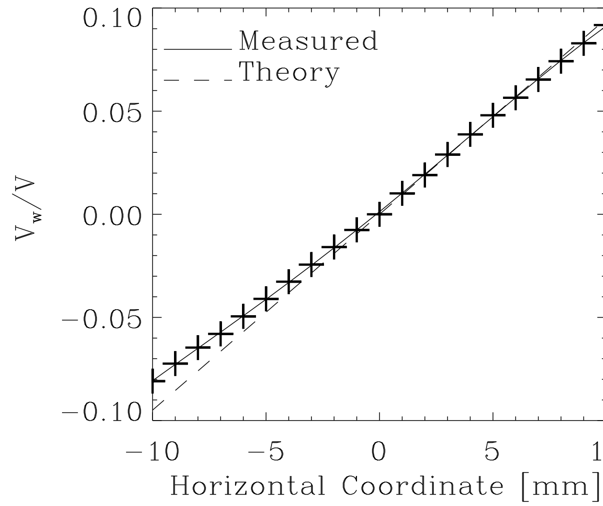

Figure 2: Measured V_w/V versus the horizontal coordinate is superposed with the results from a 2D electrostatic calculation.

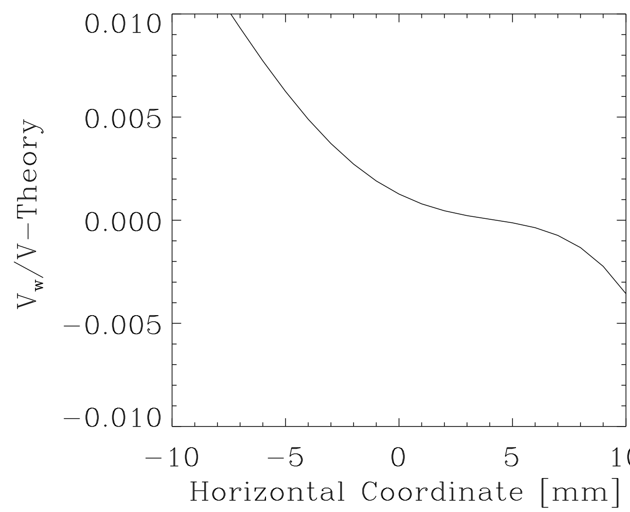

Figure 3: Plotted is the deviation of the fourth order fit to the measurements of V_w/V from the results from a 2D electrostatic calculation.

order	Laplace	Measurement
b_0	0.0	1.27×10^{-3}
b_1	9.46×10^{-3}	8.94×10^{-3}
b_2	0.0	8.18×10^{-5}
b_3	-1.41×10^{-8}	-3.39×10^{-6}
b_4	0.0	-4.10×10^{-7}

Table 1: Calculated and measured field coefficients up to the fourth order. There are defined by $V_w/V_{applied} = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4$ where x is in millimeters.

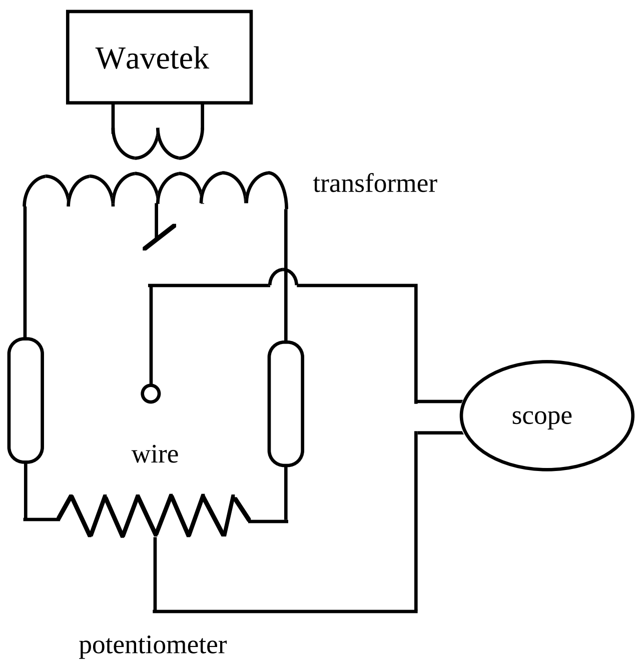

Figure 4: A somewhat simplified schematic of the circuit used to measure to excite the electrodes and measure the induced wire potential is shown.

must be antisymmetric about the mechanical center and therefore has only odd order coefficients in an expansion in x. The measured data has even order coefficients which are of comparable importance over the measurement range. Symmetry of the electrodes implies these even order coefficients cannot be accounted for by 3D end effects. One can therefore conclude that the error introduced by the 2D approximation is comparable or less than other errors. The apparent offset in figure 3 of the origin of the measured data can only be explained by the presence of even symmetry terms. In fact, it is almost entirely due to $b1$ term and the nonzero $b0$ term. Possible causes are electrode misalignments and unbalanced voltages on the electrodes. The voltage balance was set by the relative number of turns on two legs of the transformer and was not particularly accurate.

Technical Details

A simplified electrical schematic is given in figure 4. The center tap of an ordinary audio transformer is grounded to the separator vacuum chamber. A sinusoidal signal is generated by a Wavetek signal generator with a frequency between 400 and 4 kHz. This arrangement establish approximately equal and opposite voltages on the electrodes as they are normal powered. The wire is connected to a high impedance input of an oscilloscope with the common of the the scope input connected to the center tap of a good potentiometer. If there is any net charge induced on the wire it will oscillate with the applied field and cause current to flow in the high impedance input of the scope where it is easily observed. Referencing the common of the scope to the potentiometer center voltage effectively biases the wire to the potentiometer voltage. In practice since only a limited range of positions is desired an accurate fixed resistance is placed on either side of the potentiometer thereby increasing the measurement resolution. The applied source frequency should be chosen carefully to get the best results. Higher frequencies will cause larger currents to flow into the scope for the same induced charge and provide a bigger signal. However, if there frequency is too high the capacitance of the cables and impedance of the scope input tends to average out the signal and sensitivity is lost. Another complication is that the main signal circuit resonates with a broad resonance center around 10 kHz. Thus the voltage being applied to the electrodes and consequently the charge induced on wire are strong functions of frequency in this range.

References

[1] A.A. Mikhailichenko, *On the Measurement of Electric Fields Using a Rotating Probe*, Novosibirsk, Institute of Nuclear Physics preprint 84-126 (1984), In Russian