

VALIDATION OF A NOVEL EMITTANCE DIAGNOSTIC METHOD FOR BEAMS WITH SIGNIFICANT SPACE CHARGE

R.Fiorito[†], H. Zhang, O. Mete, C. Welsch, Cockcroft Institute, Daresbury, UK
 J. Power, M. Conde, N. Neveu, Argonne National Laboratory, Argonne IL, USA
 A. Shkvarunets, University of Maryland, College Park MD, USA

Abstract

Exact knowledge of beam emittance is of central importance for essentially every accelerator. However, there are only few methods to determine it when the beam has significant space charge. We report on our progress to validate a novel diagnostic method that has been proposed to determine the RMS emittance of an electron beam with space charge. This method uses RMS divergence and beam size data measured at a screen placed in a free drift region for selected values of magnetic focusing strength. A novel algorithm is then used to determine the cross correlation term and consequently the RMS emittance of the beam. Simulations, quadrupole scans, phase space tomography and optical diffraction-dielectric foil radiation interferometry are currently being employed to determine and compare the horizontal (x) and vertical (y) emittances of the 14 MeV witness electron beam at Argonne National Laboratory's Wakefield Accelerator. The results of simulations and current measurements are presented and the advantages of the new technique are discussed.

INTRODUCTION

The measurement of RMS emittance for emittance dominated beams is straight-forward and is commonly accomplished using a solenoid or quadrupole scan. For space charge dominated beams this method fails and other means must be sought. The two primary methods currently used to determine the emittance for a space charge dominated beam are the slit collimator or 'pepper-pot' technique and phase space tomography. The latter method has been shown to produce the emittance when the space charge forces are linear.

We have proposed an alternative technique to determine the emittance of a beam with significant space charge that employs both the RMS beam size and divergence data. The former is measured by directly imaging the beam; the latter can be obtained by: 1) imaging the far-field angular distribution of radiation from the beam whose visibility is a measure of the divergence; or 2) directly inferring the divergence from beam images obtained at two or more screens. In this paper we use the former method.

In contrast to phase space tomography, which usually requires a large number of beam size measurements taken with multiple focusing magnets, the new emittance method can readily be accomplished with just a few magnetic settings and only requires a single focusing element.

[†]ralph.fiorito@cockcroft.ac.uk

BACKGROUND

Novel Emittance Method

The new technique we have proposed to determine the RMS emittances for beams with significant space charge employs an algorithm to compute the cross correlation e.g. $\langle xx' \rangle$ that occurs in the equation for the RMS (x) geometric emittance

$$\varepsilon_x^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2,$$

in terms of the observables: $\langle x^2 \rangle^{1/2}$ and $\langle x'^2 \rangle^{1/2}$. This is accomplished by using the beam envelope equation [1] and taking the cross correlation term as a control variable that is iterated until the RMS beam size and divergence predicted by the envelope equation match their measured values. The method requires a minimum of two pairs of measurements at two values of focusing strength. The latter are required in order to eliminate the slope of the beam envelope entering the focusing lens from the analysis.

We have previously shown [2] that this novel method can be successfully applied to emittance dominated beams as well as beams with significant linear space charge. In the latter case the envelope equations are described by a pair of coupled nonlinear ordinary differential equations. These have been solved numerically for 1) a round beam with a symmetric focusing lens (e.g. a solenoid); 2) an elliptical beam with symmetric focusing; and 3) a round beam with asymmetric focusing. It is our goal to apply and validate this technique for the case of a real beam with significant space charge.

AWA Witness Beamline

The Argonne Wakefield Accelerator (AWA) is useful for this purpose. This machine has a 1.5 cell, L-band, RF photocathode gun operating at 60 MV/m, with emittance compensating solenoids and a magnesium photocathode. The gun generates a 7.5 MeV beam with a charge that can be varied in the range of 1-100nC per pulse by controlling the intensity of the laser used to illuminate the photocathode. The RMS normalized emittance at the gun has previously been measured using the standard pepper-pot method to be about 6 mm-mrad at a charge $Q = 1$ nC [3].

In the simulations and experiments described herein we determine the RMS emittance of the beam after its acceleration to an energy of 14.2 MeV. The laser-photocathode is setup to produce a quasi-flat-top beam

with radius $r = 2\text{mm}$, the duration of the laser/electron beam pulse $t_b = 8$ picoseconds and $Q = 1.3$ nC per pulse.

Figure 1 shows the configuration of the AWA witness beamline. Note the free drift space downstream of the linac, which contains an imaging screen (YAG2) that is used to monitor the RMS size of the beam prior to focus-

ing by quadrupoles (TQ1,2,3). The beam can be focussed by any of these quads to one of three screens: 1) YAG3, which is 25.4 mm in diameter; 2) the ODRI, which contains a screen that is 18mm in diameter; and 3) YAG4, which is 50mm in diameter and is located downstream of the screens mentioned in 1) and 2).

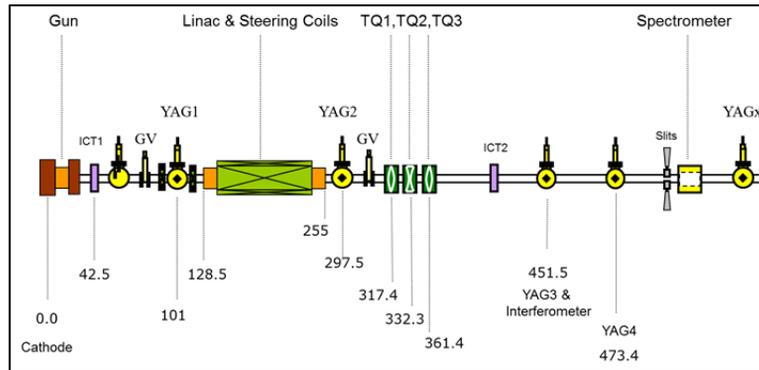


Figure 1: The AWA witness beam-line showing various elements and distances from the photocathode in units of mm.

Various other diagnostics: integrating current transformers (ICT), voltage monitors (GV), and a spectrometer are also located on the beam line.

RESULTS

Start to end simulations of the beamline have been performed with OPAL in order to predict the range of horizontal (x) and vertical (y) RMS beam sizes, divergences and emittances expected when performing TQ1,2,3 scans. The RMS size and divergences are needed to determine: 1) if the screens are sufficiently large to image the beam to 6 sigma in radius, where sigma is the result of a Gaussian fit to the measured beam distribution on a screen; 2) the range of observable ODRI fringe visibilities – the lowest measurable visibility determining the lowest value of beam divergence that can be measured from the ODRI fringe pattern [2]; 3) the range of magnetic field strengths over which the emittances are essentially constant; and 4) the focusing values for TQ1,2,3 necessary for phase space tomography [3].

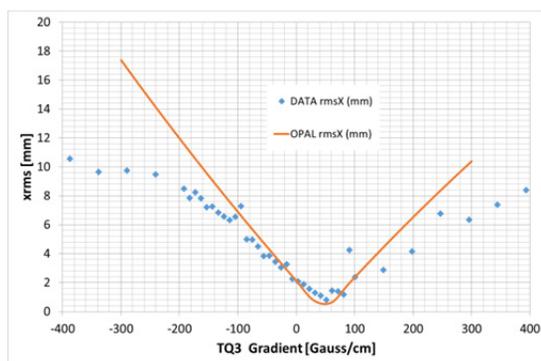


Figure 2: Horizontal RMS beam size vs. magnetic focusing strength; $Q=1.3\text{nC}$.

Figure 2 shows an OPAL-t (hereafter ‘OPAL’) simulation of the horizontal RMS beam size in orange compared with measurements.

Figure 3 presents simulated values of the normalized (x) emittance and beam size as a function of focusing gradient for a beam charge $Q=1.3\text{nC}$. Note that in the range $[-100,+100]$ Gauss/cm ($[-1,+1]$ Tesla/meter) that the x emittance is fairly constant; the y emittance is also constant in this range.

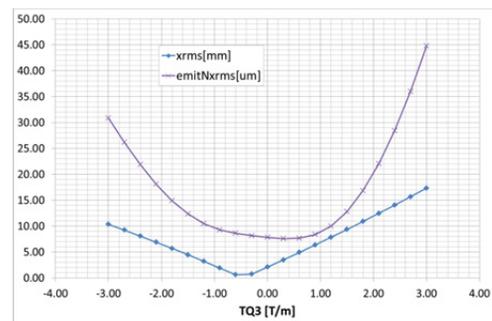


Figure 3: Horizontal (x) RMS beam size and x emittance vs. TQ3 gradient for beam with $Q = 1.3$ nC.

Figure 4 shows an expanded view of x_{rms} and x'_{rms} as a function of focusing strength predicted by OPAL. Note that in the range $[-1.0$ to $+1.0]$ Tesla/m, x'_{rms} varies from 0.2 – 4.5 mrad. Since the range of sensitivity of the presently installed ODR interferometer to beam divergence is 0.3 – 3 mrad, there is a good overlap of focusing values, where the new emittance method can be tested. Similar results are predicted for the vertical divergence y' as well.

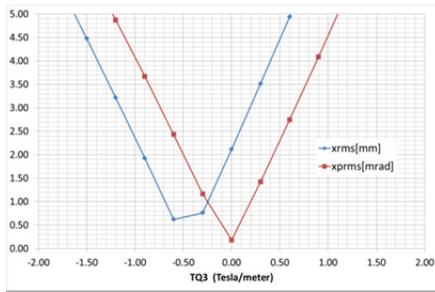


Figure 4: Horizontal RMS beam size and divergence vs. TQ3 quadrupole strength.

Figure 5 shows a comparison of measured RMS horizontal beam sizes at YAG3 with those predicted by the envelope equation [4], using the beam size and divergence, predicted by OPAL at YAG2 assuming an x emittance of 8 microns (see Figure 1).

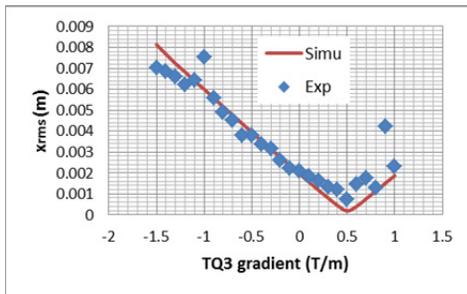


Figure 5: Horizontal RMS beam size vs. quadrupole (TQ3) gradient (Tesla/meter).

Figure 6, shows a simulated reconstructed (x, x') trace space plot of the beam at the location of YAG2 shown in Figure 1. The beam images used to reconstruct the trace space were generated at YAG4 using OPAL.

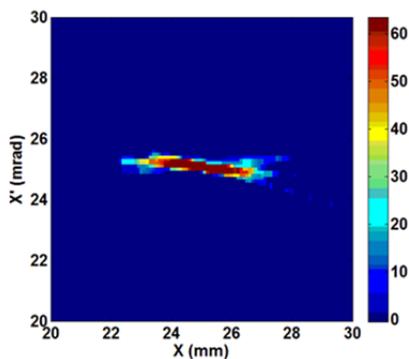


Figure 6: Trace space (x, x') reconstruction using OPAL simulated beam images generated at YAG4.

Three quadrupole were used to generate a full 180 degrees of rotation. Furthermore, one degree steps are necessary to reduce any artefacts in the reconstructed trace space distributions. From this data we have computed the RMS values of the x beam size, 1.44mm; the x' divergence, 0.223mrad; and the x normalized emittance, 8.4

mm mrad. The latter is in reasonably good agreement with the values of emittance simulated by OPAL and those used to compare quantities generated by the envelope equation with data as shown in Figure 5.

Two techniques are currently being applied to directly measure the (x, y) beam emittances of the AWA beam: phase space tomography [4] and ODRI [5]. The former will provide the experimental basis for the validation of the new emittance diagnostic technique; the latter will provide simultaneously measurements of both the RMS beam size and divergence at two or more values of quad focussing strength – the components necessary to employ the new emittance algorithm. The results of both experimental techniques can then be directly compared to the OPAL predicted trace space plots and emittances.

CONCLUSIONS

We have performed OPAL simulations and preliminary quadrupole scans of the AWA witness beam line that provide essential information to test and validate a new emittance monitoring technique for beams with space charge. These include the range of magnetic focussing values where the emittance is constant; and the range of beam sizes and divergences that can be measured by the screens and ODR interferometer currently installed.

Within these limits OPAL shows a good fit to experimental quadrupole scan data and produces an emittance value that is consistent with previous measurements taken with the pepper-pot technique. They are also in good agreement with those obtained using the envelope equation. In addition, trace space maps of the AWA beam have been successfully simulated using OPAL.

Phase space tomography measurements are currently underway at AWA to provide bench mark experimental values of the x and y emittances. These values will then be used to validate the new emittance method.

The new emittance diagnostic method has significant advantages over the two standard techniques used to determine the emittance of a space charge dominated beam, i.e. 1) the pepper pot technique, which requires collimation of the beam particles; and 2) phase space tomography, which requires up to 180 measurements and multiple quads in order to produce trace space maps sufficiently free of numerical artefacts. In contrast to 1) and 2), the new technique does not require any beam collimation and only needs only a few focussing settings with a single magnet.

ACKNOWLEDGEMENTS

Work supported by the EU under grant agreement 624890, the STFC Cockcroft Institute Core Grant No. ST/G008248/1.

REFERENCES

- [1] M. Reiser, *Theory and Design of Charged Particle Beams*, 2nd Ed., J. Wiley-VCH, 2008.

- [2] K. Poorrezaie, R. Fiorito, R. Kishek, B. Beaudoin, PRAB 16, 082801, 2013.
- [3] J. Power, M. Conde, W. Gai, F. Gao, R. Konecny, W. Liu, Z. Yusof, in *Proc. PAC'07*, Albuquerque, NM, USA, June 2007, paper FRPMN117.
- [4] D. Stratakis, R. Kishek, H. Li, S. Bernal, M. Walter, B. Quinn, M. Reiser, and P. O'Shea, *Phys. Rev. ST Accel. and Beams*, vol. 9, 112801, 2006.
- [5] A. Shkvarunets, R. Fiorito and P. O'Shea, in *Proc. PAC'07*, Albuquerque, NM, USA, June 2007, Paper FRPM034.