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TRANSVERSE UNCORRELATED EMITTANCE DIAGNOSTIC FOR MAGNETIZED ELECTRON BEAMS

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Abstract

The study of magnetized electron beam has become a high priority for its use in ion beam cooling as part of Electron Ion Colliders and the potential of easily forming flat beams for various applications. In this paper, a new diagnostic is described with the purpose of studying transverse magnetized beam properties. The device is a modification to the classic pepper-pot, used in this novel context to measure the uncorrelated components of transverse emittance in addition to the typical effective emittance. The limitations of traditional methods are discussed, and simulated demonstrations of the new technique shown.

INTRODUCTION

Research at Thomas Jefferson National Accelerator Facility (JLab) has focused on the production of magnetized electron beams [1,2] for the purpose of an electron cooler for the Jefferson Laboratory Electron Ion Collider (JLEIC) [3]. Magnetized electron bunches are generated when the source cathode is immersed within a magnetic field that has a perpendicular field component, typically provided by one or more solenoids. Due to the conservation of momentum, electrons gain angular momentum as they exit the magnetic field.

It is estimated that the cooling rate between a co-propagating electron and ion beam in a solenoid channel could be improved by about two orders of magnitude if the electron bunch was not following typical Larmor rotations [4,5]. To investigate magnetized beam, a short diagnostic beam-line has been constructed to characterize the electron beam as a function of magnetization, as shown in Fig. 1.

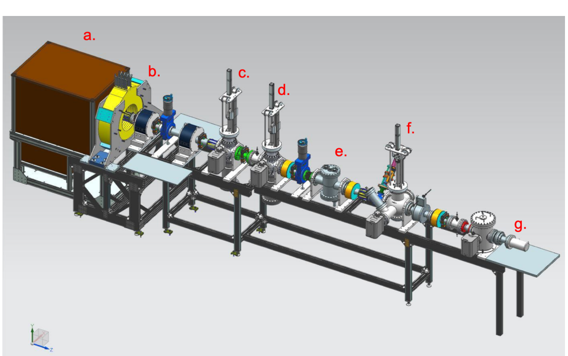

Figure 1: Diagnostic beamline: a. Gun in faraday cage, b. Magnetizing solenoid, c. Viewer 1, d. Viewer 2/1DPP, e. DQW Cavity, f. Viewer 3, g. Beam dump.

The inherent angular momentum of magnetized beams manifests as a rotation and natural divergence in the transverse plane that complicates traditional diagnostic techniques, as described in the following sections. It is extremely important to be able to measure the uncorrelated emittance for the JLEIC electron cooler because this is the emittance present inside the cooling solenoid when co-propagating with the ion beam.

EMITTANCE

For the JLEIC cooler, the canonical transverse emittance, ε_m, is set at 36μm. In addition to the magnetized emittance, which has a linear correlation in the x, ρ_y and y, ρ_x planes (alternatively r, ρ_ϕ), there is the typical uncorrelated emittance, ε_u, from thermal electron energy at the cathode, non-linear fields and induced by space-charge forces within the bunch. For the JLEIC cooler there is a budget of 19μm for the uncorrelated emittance component. Minimizing this quantity decreases the chance of undesirable electron-ion recombination [6]. The total effective emittance, ε, is given by:

$$\varepsilon^2 = \varepsilon_m^2 + \varepsilon_u^2 \quad (1)$$

Emittance Diagnostics

Emittance measurement techniques at low energy typically involve a insertable mask that allows a small portion of the beam to be transported (without space-charge forces) to a viewer, wire scanner or Faraday cup [7]. The emittance is then derived either statistically from the sampled beam or from an interpolated reconstruction of phase space. These masks are usually either slits or 2D pepper-pots. Single or multi-slits can be used to measure a 2D transverse phase space, while a pepper pot can measure both transverse planes simultaneously.

Consider a single slit diagnostic, where the beam is scanned over the aperture. A beamlet is passed through the slit and is incident on a viewer. In the case of magnetized beams, this beamlet is rotated and generally large at the viewer compared to non-magnetized beams because of the angular momentum. The emittance can be calculated by statistically evaluating the first and second moments of position and angle, or a profile can be fitted to the divergent dimension of each beamlet and used to reconstruct phase space [8,9].

Multi-slits and 2D pepper-pots can be problematic with highly divergent beams as beamlets can overlap and one has to choose a method of chopping the image to assign a portion

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to each slit or hole for calculation. If the divergence is non-uniform across the radius of the beam or asymmetric, though not impossible, the image division for analysis becomes more subjective.

At JLab as part of a magnetized beam test from a thermionic gun a 1D pepper-pot, shown in Fig. 2, was designed as a longitudinal bunch profile diagnostic. The 1D pepper-pot has distinct advantages for longitudinal measurements as described in [10]. For magnetized beams the 1D pepper-pot can also be used to provide both transverse phase space images when combined with beam scanning in both the horizontal and vertical plane. Figure 3 shows the typical behavior of beamlets as simulated from a 1D pepper-pot.

The images displays some slight rotation because the center of the bunch is at the mask location and the head, downstream, is already diverging.

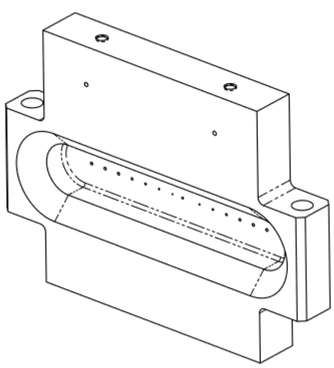

Figure 2: Mechanical design of 1 dimensional pepper-pot.

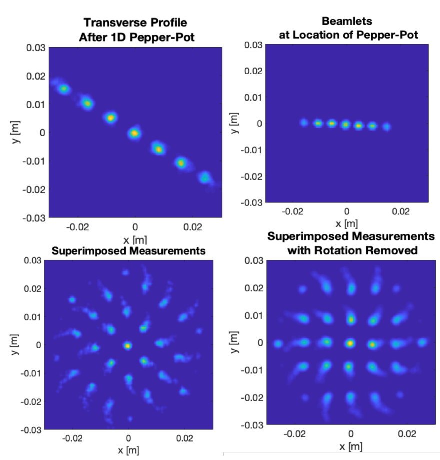

Figure 3: Example of simulated beamlets from the pepper-pot as would be seen on viewer screen for measurements.

The 1D pepper-pot has been designed with an array of 15 horizontal holes spaced such that beamlets will not overlap for a large operating region. For vertical emittance measurements, the beam is scanned over the pepper-pot vertically using carefully calibrated steering magnets. Shown in Fig. 3 is a simulation of a beam image on the viewer, combined for 5 vertical positions. The analysis to reproduce phase space (or statistically calculate emittance) requires that each beamlet be assessed individually. With this design, one can mask unwanted beamlets without losing information. For each beamlet the first and second moments in the x and y plane of the viewer are evaluated and an intensity profile taken. Over many vertical measurements, one can reconstruct vertical phase space at the location of the diagnostic.

By changing perspective of the image shown one can view the line of holes in the average rotated plane to gain insight into the uncorrelated emittance. By calculating the average rotation and removing this from the image, then the procedure of dividing each beamlet and calculating profiles and moments is repeated. Now, the total vertical uncorrelated emittance is revealed, $\varepsilon_{u,y}$. The horizontal emittances, ε_x and $\varepsilon_{u,x}$ require additional horizontal beam scanning to create more data points between each horizontal hole.

SIMULATION

The beamline shown in Fig. 1 has been simulated using the particle tracking code GPT [11]. Figure 4 depicts the normalized rms effective emittance and the uncorrelated component. The rms uncorrelated emittance is calculated by fitting a least-square method line of best fit, with gradient m to the (y, ρ_x) phase space and calculating non-rotated momenta: $\rho_y = \rho_{y0} - mx$ where ρ_{y0} is the original momentum.

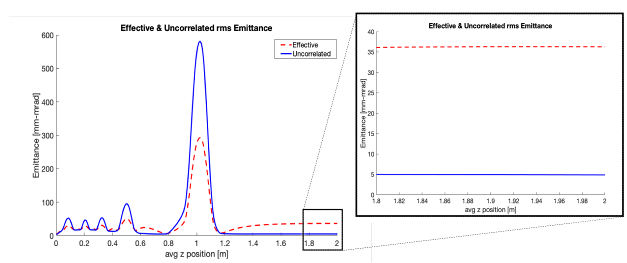

Figure 4: Effective rms emittance (red), uncorrelated rms emittance (blue) evolution from cathode to 1D pepper-pot.

To demonstrate how this diagnostic would be used in practice, a virtual experiment in simulation was performed utilizing the 1D pepper-pot. The phase space for the effective emittance and the uncorrelated emittance as simulated directly from GPT are compared with the reconstruction from the virtual experiment. These are shown in Fig. 5.

The calculated effective emittance from the reconstruction is 36.24μm, compared to 36.08μm directly from the simulation. The calculated uncorrelated emittance from the reconstruction is 5.03μm, compared to 4.91μm directly from the simulation. Even with only ~1% of the beam being sampled for use in reconstruction, the effective emittance is within 0.5% accuracy. Visual comparison also shows good agreement. The uncorrelated emittance is within 2.5% accuracy. There is a larger discrepancy between the simulated and reconstructed uncorrelated emittance due in part to the tails on the beamlets from the non-linear rotation present on the transverse edge of the bunch. Only the linear rotation is

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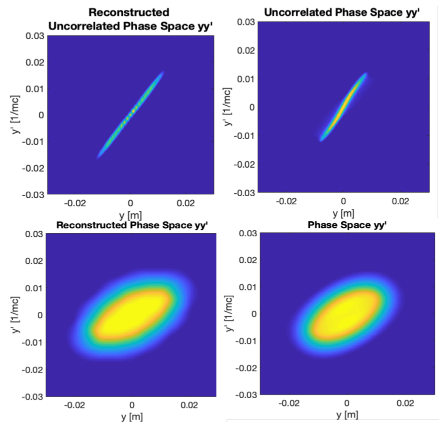

Figure 5: Recreated phase space from simulated measurements.

removed. Therefore, the non-linear tails of the beamlets on the rotated image increase the measured emittance giving an overestimation of the true uncorrelated emittance. These tails could be artificially removed to potentially give better agreement in measurement.

OUTLOOK

The pepper-pot has been installed in the diagnostic beamline and initial commissioning tests have been performed to ensure it functions as designed. Figure 6 shows a composite image of 5 real measurement scans taken of a non-magnetized beam with the pepper-pot. These real commissioning tests were done without the magnetization used in the simulated measurements. Shown in Fig. 7 is the simulated measurement with the rotation from magnetization removed, in order to have a better visual comparison. Removing the rotation does not remove the beamlet tails from non-linear dynamics and because the real test measurements were never magnetized, Fig. 6 will not have the non-linear tails that are seen in Fig. 7.

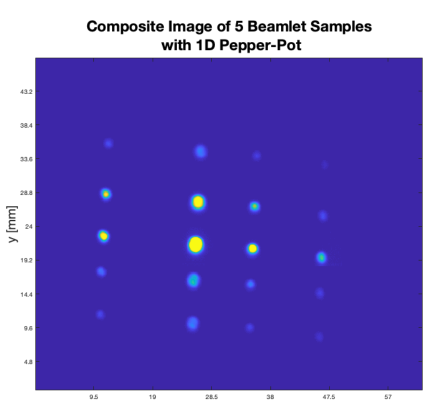

Figure 6: Composite image of five real viewer images collected using the pepper-pot in the diagnostic beamline. The tilt is not from magnetization, but from pepper-pot misalignment.

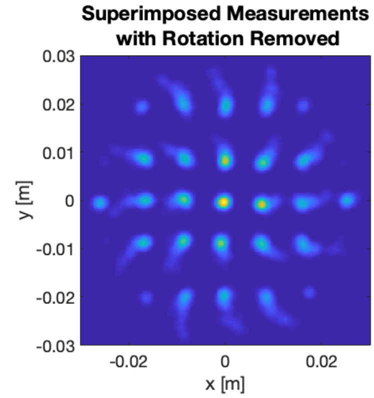

Figure 7: Composite image of five simulated measurements of beam with roation form magentization removed.

However, the similarities between the simulated measurements and the real images are evident. The commissioning processes was successful. The remaining work is to perform a full measurement and phase space reconstruction of a beam from a magnetized beam matching our simulation conditions such as the appropriate 36μm emittance. Under these conditions we will see a better match to simulation and the full benefits of the 1DPP will be demonstrated.

CONCLUSION

The simulation results and initial commissioning work demonstrates that a 1D pepper pot is a new diagnostic that can be utilized to reconstruct and visualize the uncorrelated transverse phase space component of magnetized beams in addition to the traditionally viewed effective phase space. With beam scanning horizontally and vertically, both transverse planes can uniquely be generated with this diagnostic.

There is a further advantage of the 1D pepper pot over a slit diagnostic when simply looking at a rotated image downstream, in that the magnetization of the beam in the transverse (r, ρ_ϕ) plane can be assessed also.

For the success of the JLEIC cooling scheme it is critical to know that the magnetization of the beam has been preserved from the cathode and that the uncorrelated component of transverse phase space is within specification. In the low energy (<10MeV) region, this novel diagnostic yields quantitative information on both of these parameters.

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