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RECONSTRUCTING 4D SOURCE MOMENTUM SPACE VIA APERTURE SCANS *

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Abstract

The brightness of the beam in any linear accelerator can be no greater than at its source. Thus characterization of source initial conditions, including spatial and momentum distributions, is then critical to understand brightness evolution in a linac. Often measurement of the initial momentum distribution is hampered by imperfect knowledge of either the spatial source distribution or the downstream particle optics. Here we describe a method of recovering the transverse momentum space of a beam at the particle source without prior knowledge of the electron optics used to obtain the phase space or any source parameters; only linearity of the transport is assumed. We then demonstrate this method experimentally by measuring a 4D phase space using an aperture scan and subsequently recover the transverse phase space of a beam emitted by an alkali antimonide photocathode.

INTRODUCTION

The need for brighter electron beams in applications such as free electron lasers and ultrafast electron microscopy [1] requires advances in electron sources. One particular avenue for achieving brighter beams is developing photocathodes with smaller transverse momentum spread, which is often measured by a figure of merit known as the mean transverse energy (MTE) defined as,

$$\mathrm{MTE} = \frac{\langle p_\perp^2 \rangle}{2m_e}, \tag{1}$$

where $p_\perp$ is the transverse momentum and m_e is the electron mass. MTE is often inferred by first measuring either the 2D or 4D transverse beam emittance in a dedicated diagnostic after an emittance preserving transport section. To determine MTE, some knowledge of the source spatial distribution is required; often one assumes the spatial source distribution is in one-to-one correspondence with the photocathode drive laser distribution at the cathode [2]. However, this assumption may be violated in cases where photoemission is partially nonlinear or where the photoemission source has a spatially varying efficiency, in which cases *a-proiri* knowledge of the source spatial distribution may be impossible. Compounding difficulties further, sufficient knowledge of the linear transport matrix from source to emittance diagnostic may be challenging to achieve to do the presence of unwanted fields.

Here, we will present a method for reconstructing the momentum space of the beam at the photocathode that does not require detailed knowledge of the photoemission process or the beamline elements. We only assume that the transport from source to diagnostic is linear and symplectic. The proceeding is structured as follows. First, we discuss the utility of the symplectic condition for our method. Then we will discuss the reconstruction method in detail, including the use of aperture scans to experimentally measure the 4D transverse phase space of the beam. Finally, we apply the reconstruction method and analyze the resulting momentum space for an alkali antimonide photocathode in a test beamline.

SYMPLECTICITY

A linac source is a Hamiltonian system that evolves according to Hamilton's equations, which can be expressed in symplectic form as,

$$\mathbf{x}' = \mathbf{\Omega}\frac{\partial \mathcal{H}}{\partial \mathbf{x}}, \tag{2}$$

where $\mathbf{x}$ is a phase space vector containing positions and momenta $(q_1, p_1, ..., q_N, p_N)$ for N degrees of freedom, $\mathbf{x}'$ is the derivative of this vector with respect to the longitudinal coordinate, and $\mathcal{H}$ is the Hamiltonian. The matrix $\mathbf{\Omega}$ is a $2N$ x $2N$ matrix given by,

$$\mathbf{\Omega} = \begin{pmatrix} 0 & 1 & & & \mathbf{0} \\ -1 & 0 & & & \\ & & \ddots & & \\ & & & 0 & 1 \\ & \mathbf{0} & & -1 & 0 \end{pmatrix} \tag{3}$$

For a transport system from source to diagnostic which is fully linear, the final position and momentum of a particle $\mathbf{x_f}$ at the diagnostic is expressed as a transfer matrix $\mathbf{R}$ acting on its initial position and momentum $\mathbf{x_i}$ as such, $\mathbf{x_f} = \mathbf{R}\mathbf{x_i}$. The Hamitonian nature of the transport requires that the transfer matrix $\mathbf{R}$ must then satisfy the symplectic condition $\mathbf{R}^T\mathbf{\Omega}\mathbf{R} = \mathbf{\Omega}$.

RECONSTRUCTION METHOD

For the remainder of this proceeding, we will only consider the 4D transverse phase space where the coordinates of a particle is given by $\mathbf{x} = (x, p_x, y, p_y)$. We will first summarize the method qualitatively and then proceed to

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describe it quantitatively. We first make a measurement of the 4D phase space of the beam, for example by the aperture technique described below. We then displace the emission transversely by a known amount (for example, by moving the laser by a known amount on the photocathode). While the distribution of the laser may be unknown in some cases, it may still be possible to generate a known transverse displacement of the emission centroid. By measuring a second 4D phase space, we can compute the phase space displacement at the diagnostic corresponding to this change, yielding for example R_{11} and R_{21}. By measuring several additional phase spaces corresponding to known laser displacements, one can thereby measure all transfer matrix elements $R_{i,1}$ and $R_{i,2}$, where i is any integer from 1 to 4. We will show that by using the symplectic matrix $\mathbf{\Omega}$ as an *operator* on the measured phase space distributions, we can get retrieve the distributions of the momentum conjugate to coordinates in which the laser had been displaced. At this stage one may then reconstruct the entire initial momentum distribution

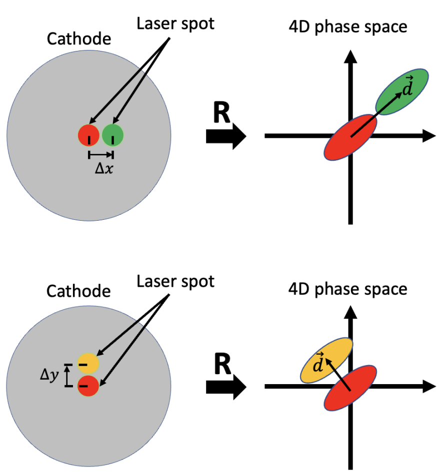

Figure 1: Moving the emission (laser spot here) by a known amount results in a measurable displacement in the phase space of a beam at the end of a beamline. With the emission and phase space displacements, the entire initial 4D phase space can be reconstructed.

Now we turn to to a quantitative description. Let us apply an arbitrary spatial displacement $\Delta x\hat{x}$ to the initial photocathode phase space, which can be done by moving the laser spot on the photocathode as in Fig. 1. This results in a displacement in the final phase space measured at the end of the beamline $\mathbf{d} = \mathbf{R}\Delta x\hat{x}$. Along with the symplectic condition mentioned previously, we can derive the following expression (see appendix for more details) for the initial momentum along the $\hat{x}$ direction, $p_{x,i}$,

$$p_{x,i} = \frac{1}{\Delta x}\mathbf{d}^T\mathbf{\Omega}\mathbf{x_f}. \tag{4}$$

Thus for each phase space point measured at the diagnostic $\mathbf{x_f}$ we determine the source momentum in the direction of the laser's displacement $p_{x,i}$. We can follow a similar derivation to obtain the initial momentum in the orthogonal $\hat{y}$ direction, $p_{y,i}$, and subsequently reconstruct the entire initial transverse momentum space at the photocathode.

4D APERTURE SCANS

The most important tool required in this momentum reconstruction is the ability to measure a 4D transverse phase space. We measure this by rastering the beam across a small aperture, and recording the remaining beamlet's location and appearance on a downstream viewscreen. The beamline used for this is shown in Fig. 2 (a). Electrons are emitted from a thin film Cs_1Sb photocathode, where photoemission is driven by a 405 nm wavelength laser that is passed through a 200 um pinhole and subsequently imaged with a convex lens to a spot size of roughly 50 um rms on the cathode. The emitted electrons are then accelerated with a DC gun biased to 15 kV and enter a transversely focusing solenoid that focuses the beam onto a 70 um aperture. A corrector coil (C1) applies a dipole field that steers the beam across the aperture in both transverse directions. The transmitted beamlet expands in a drift section and is steered back onto the detector using another corrector coil (C2), which is left unchanged during the scan. The detector is made of a YAG screen and a scientific CMOS camera. The detector's spatial resolution combined with the drift length give our setup an angular resolution of ~70 μrad. The 4D phase space is reconstructed by shifting and combining the individual beamlet profiles, stacking them together into a 4D distribution.

RESULTS

The aperture scans yield a 4D phase space distribution which is shown in Fig. 2 (b). To remove contributions from camera noise, light pollution, stray electrons, and etc. we performed noise thresholding on the 4D phase space distribution, where all values in the 4D phase space distribution lower than some noise threshold are set to zero. Further analysis of this thresholding procedure and comparison to other noise reduction methods is ongoing.

In order to perform the momentum reconstruction method as outlined previously, we must repeat the aperture scan for multiple laser positions on the cathode and then find how the centroid of the distribution has changed. For these scans, the detailed 4D phase space is not important, instead only this centroid displacement will be used in the reconstruction. Since the laser displacements are not purely orthogonal, we use linear regression to fit the phase space displacement to the form $\mathbf{d} = \mathbf{A}\mathbf{r_l} + \mathbf{b}$, where $\mathbf{d}$ again refers to the phase space centroid and $\mathbf{r_l}$ refers to the laser displacements. Using the linear regression fit, we can now apply the momentum reconstruction method, and obtain the momentum space at the cathode as shown in Fig. 3.

We note that the reconstructed cathode momentum space is asymmetric, which is not expected for photoemission from a polycrystalline surface. This is very likely to be an artifact of our measurement, and we are currently working to resolve this. One of the potential causes for the momentum asymmetry may be an unknown stray quadrupole field between

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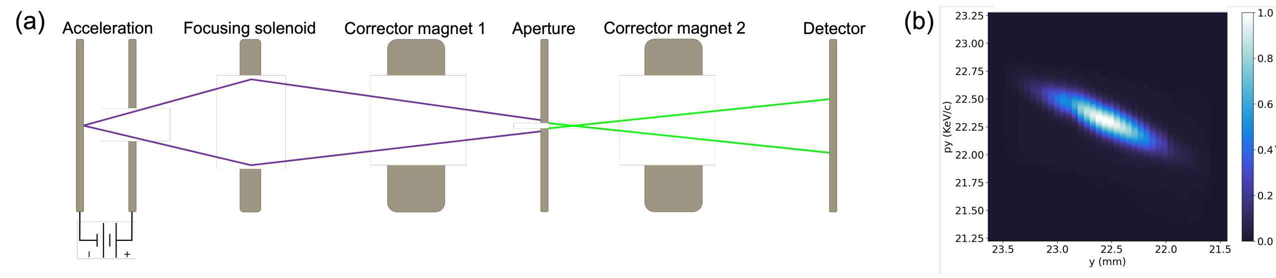

Figure 2: (a) Layout of the Cornell MTE-Meter beamline. Beam (purple) is scanned across the aperture and the transmitted beamlet (green) is imaged by the detector. (b) 2D projection of the measured 4D phase space along y-py coordinates.

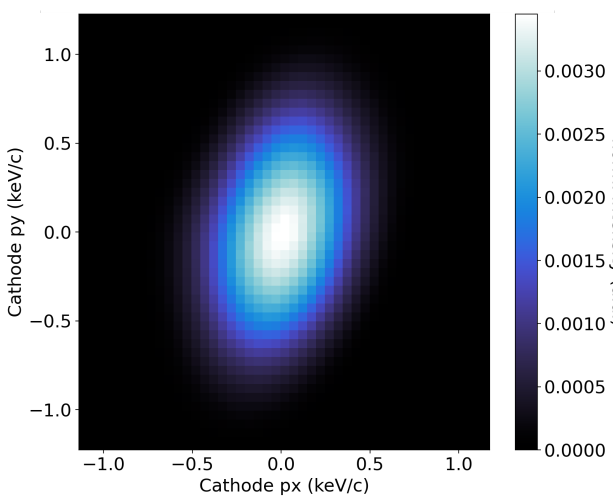

Figure 3: Reconstructed momentum space at the cathode. The asymmetry between the momentum spreads in p_x and p_y, as well as the $\langle p_x p_y \rangle$ correlation, may be caused by stray quadrupole fields in the beamline.

the aperture and YaG screen detector. Our 4D phase space measurement assumes that this section is a pure drift, so that the appearance of the beamlet on the screen is a direct measure of the momentum distribution of that beamlet. We circumvent this problem by defining an average rms momentum σ_p, motivated by the definition of emittance (see details in appendix).

$$\sigma_p = \left(\langle p_x^2 \rangle \langle p_y^2 \rangle - \langle p_x p_y \rangle^2 \right)^{1/4}. \tag{5}$$

In the same way that emittance is preserved after sheer transformations to the phase space, simulations suggest that this definition is more robust to the sheering effects of a stray quadrupole field. The MTE is now defined as MTE = σ_p^2/m_e, m_e is electron mass. This definition of the MTE yields of ~ 230 meV, which is reasonable for this cathode with excitation in the blue.

CONCLUSION

We've introduced a novel method to recover initial cathode momentum distributions without explicit knowledge of the transfer matrix. We instead rely on known displacements of the initial beam centroid position, which in many cases may be easier to determine than the exact spatial details of the source spatial distribution. We derive analytically and show experimentally this process at work in measurements of Cs_1Sb via a simple transport channel and aperture-based phase space scans.

APPENDIX

Deriving Momentum Reconstruction

For a 4D phase space, there are $N = 2$ degrees of freedom. As such, the $\mathbf{\Omega}$ matrix is given by,

$$\mathbf{\Omega} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}.$$

Multiplying $\mathbf{d}^T$ by $\mathbf{\Omega x_f}$ then gives,

$$\begin{aligned} \mathbf{d}^T \mathbf{\Omega x_f} &= \Delta x \hat{x}^T \mathbf{R}^T \mathbf{\Omega R x_i} = \Delta x \hat{x}^T \mathbf{\Omega x_i} \\ &= \Delta x \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} x_i \\ p_{x,i} \\ y_i \\ p_{y,i} \end{pmatrix} \\ &= \Delta x \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} p_{x,i} \\ -x_i \\ p_{y,i} \\ -y_i \end{pmatrix} \\ &= \Delta x p_{x,i} \\ \implies p_{x,i} &= \frac{1}{\Delta x} \mathbf{d}^T \mathbf{\Omega x_f} \end{aligned}$$

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