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THE FLAT BEAM EXPERIMENT AT THE FNAL PHOTOINJECTOR

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Abstract

A technique for production of an electron beam with a high transverse emittance ratio, a "flat" beam, has been proposed by Brinkmann, Derbenev, and Flöttmann.[1] The cathode of an RF-laser gun is immersed in a solenoidal magnetic field; as a result the beam emitted from a round laser spot has a net angular momentum. Subsequent passage through a matched quadrupole channel that has a 90 degree difference in phase advance between the transverse degrees of freedom results in a flat beam. Experimental study is underway at the Fermilab Photoinjector. Thus far, transverse emittance ratios as high as 50 have been observed, and the results are in substantial agreement with simulation.

1 INTRODUCTION

Two years ago, Ya. Derbenev invented an optics maneuver for transforming a beam with a high ratio of horizontal to vertical emittance—a "flat beam" —to one with equal emittances in the transverse degrees-of-freedom—a "round beam".[2] High energy electron cooling at the TeV energy scale was the motivation.

Last year, R. Brinkmann and K. Flöttmann of DESY joined with Derbenev in a paper that reverses the process—obtain a flat beam from a round beam produced from the cathode of an electron gun.[1] This could be a significant step toward the elimination or simplification of the electron damping ring in a linear collider design. The other major step in that process is the delivery of polarized electrons in the flat beam, and this is an R&D challenge beyond the scope of the work reported here.

The intent of the present experiment was to demonstrate the round-to-flat transformation, compare the results with simulation, and verify that the demonstration was not obscured by other processes. In the following sections, we present a simplified version of the transformation, describe the experimental setup, present the results, and comment on future plans.

2 PRINCIPLE

Suppose that the cathode of an electron gun is immersed in a uniform solenoidal field of magnitude B_z. For the sake of this argument, assume that the thermal emittance is negligible and ignore RF focusing in the gun. Then the particles just stream along the field lines until the end of the solenoid is reached, at which point the beam acquires an angular momentum. A particle with initial transverse coordinates x_0, y_0 acquires angular deflections. With momentum p_0 at the solenoid end, the state of the particle becomes

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}_0 = \begin{pmatrix} x_0 \\ -ky_0 \\ y_0 \\ kx_0 \end{pmatrix}$$

where

$$k \equiv \frac{1}{2}\frac{B_z}{(p_0/e)}.$$

Next pass the beam through an alternating gradient quadrupole channel. Assume that the channel is represented by an identity matrix in the x-direction and has an additional 90^0 phase advance in y.

We get the output state

$$\begin{aligned} \begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \beta \\ 0 & 0 & -\frac{1}{\beta} & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ -ky_0 \\ y_0 \\ kx_0 \end{pmatrix} \\ &= \begin{pmatrix} x_0 \\ -ky_0 \\ k\beta x_0 \\ -\frac{1}{\beta}y_0 \end{pmatrix} \overset{\beta=1/k}{\rightarrow} \begin{pmatrix} x_0 \\ -ky_0 \\ x_0 \\ -ky_0 \end{pmatrix}. \end{aligned}$$

In the last step above, with $\beta = 1/k$, the particles end up with equal displacements in x and y and travelling at equal angles in x and y. This describes a flat beam inclined at an angle of 45^0 to the coordinate axes. Change to a skew-quadrupole channel, and the flat beam can be aligned along either the horizontal or vertical axis.

This idealized example is only meant to illustrate the principle. The essential points about the quadrupole channel are the $\pi/2$ difference in phase advance between the transverse degrees-of-freedom, and the match of the Courant-Snyder parameters.[3] This may be accomplished with as few as three quadrupoles. Of course, in practice, RF focusing fields in the gun and in a booster cavity, space charge, and so on cannot be ignored.

With the inclusion of thermal emittance, Brinkmann, Derbenev, and Flöttmann[1] speak of an achievable emittance ratio of order 10^2 or more for a beam with normalized emittance $\sqrt{\epsilon_x \cdot \epsilon_y} \approx 1\mu$m per nC of bunch charge. The expression for the emittance ratio is

$$\frac{\epsilon_x}{\epsilon_y} \approx \frac{4k^2\sigma_c^2}{\sigma_c'^2}$$

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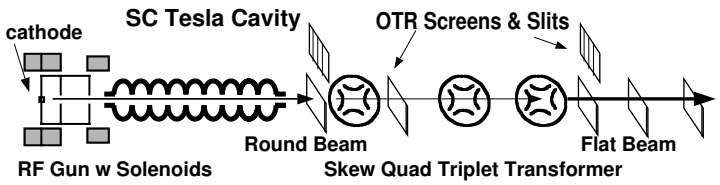

Figure 1: Very schematic rendition of the layout at Fermilab related to this experiment.

where now in the definition of k, B_z remains the field on the cathode, but p_0 is the momentum at entry to the quadrupole channel, and σ_c, σ_c' are the standard deviations of the distribution in displacement and angle at the cathode. The resulting vertical emittance would be 0.1 μm, in the range of interest for a linear collider. Liouville's Theorem remains in effect for the 4-dimensional transverse emittance, but the angular momentum provides the lever by which emittance may be moved from one degree-of-freedom to another.

3 THE FERMILAB PHOTOINJECTOR ENVIRONMENT

The photoinjector at Fermilab is well suited to this sort of experiment. The RF gun delivers electrons with a kinetic energy of (typically) 3.8 MeV. The superconducting booster cavity raises the electron energy to 17 MeV.

The solenoid is composed of three separately excited coils permitting fields at the cathode in the range 0 to 2.7 kG. The coil immediately upstream of the cathode, the "bucker", is normally excited with current opposite to that of the next coil, the "primary" to produce zero field at the cathode. Downstream, the combination yields solenoidal focusing, which can be adjusted with the third coil, the "secondary". The secondary has little effect on the field on the cathode.

Following the booster cavity, about 8 meters of beamline are available for experiments. There are 11 quadrupoles that are easily moved about or rotated into the skew orientation. A dozen view screens are situated on the line, and there are three locations where slits are installed for emittance measurement. The laser can operate at a variety of pulse lengths up to 12 ps, the setting that we used. Bunch charge as high as 10 nC is available. We operated at no higher than 1 nC in order to reduce space charge effects as much as possible. The layout as related to this experiment is sketched in Fig. 1.

4 PROCEDURE

The solenoid coils were set to produce a field at the cathode in the expected range, about 0.75 kG. Using the language of the preceding section, this meant setting the bucker to zero current and controlling the cathode field with the primary. The beam was observed at the location of the two screens immediately downstream of the booster cavity, and by adjustment of the secondary coil, the beam spot was made the same size at these two places. In other words, a beam waist was produced. At this stage, the beam has a round shape on the screens.

The simple argument of Sec. 2 is no longer valid for determination of the β for the match, because the solenoid field is not uniform and the RF focusing and acceleration must be taken into account. Making use of linearity, axial symmetry, and the conservation of canonical angular momentum between the cathode and the waist yields for the value of β at entry to the quadrupole channel

$$\beta = \frac{\sigma_w^2}{\sigma_c^2}\frac{2(p_w/e)}{B_c}$$

where the subscripts c and w refer to the cathode and waist respectively and the σ's characterize the radii of the beam spots. The other Courant-Snyder parameter involved in the match, α, is zero due to the choice of a waist as the match point.

Given preliminary values for the matching parameters, an (asymmetric) skew triplet was set up. Flat beam profiles were rather easily achieved by adjustment of available tuning parameters, including the launch phase from the RF gun. The latter proved to be particularly important, a circumstance that is yet to be explained.

5 RESULTS

The transformation should work — it's linear dynamics — and it does. The match and phase difference were achieved with three skew quadrupoles. The beam image on an OTR screen 1.2 m downstream of the third quadrupole is shown in Fig. 2; the beam width is an order of magnitude larger than the height. A critical observation is that the beam remain flat as it drifts farther downstream. That it does is demonstrated in Fig. 3 near the end of the beamline at 3.6 m from the third quadrupole.

In Fig. 2 there is a hint of an s-shape, which likely indicates that spherical aberrations (e.g. space charge) are at work. If the solenoid field on the cathode is varied up or down from the matched condition the beam apparently rotates clockwise or counterclockwise as it drifts, indicating that the angular momentum is no longer completely cancelled. Of course, it isn't a real rotation — there's no torque— it's a shear.

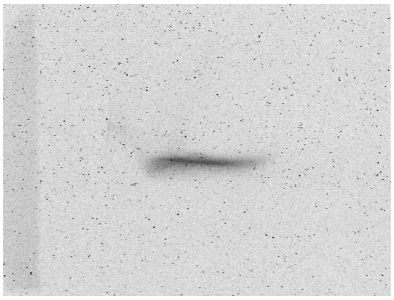

Figure 2: Beam profile on OTR screen 1.2 m downstream of the third skew quadrupole.

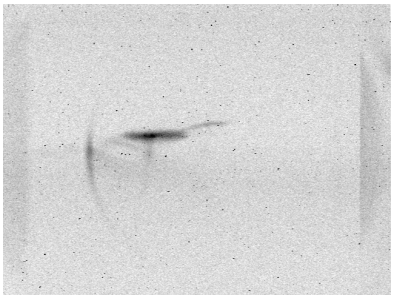

Figure 3: Beam profile on OTR screen 3.6 m downstream of the third skew quadrupole. Dark current is visible to the right of the main beam image.

In these figures, the beam is flat in the horizontal plane. The OTR screens are viewed from the side, and so a beam that is flat horizontally presents a depth of field problem for best emittance analysis. So in later stages of the experiment, the beam was made flat in the vertical plane. From slit data in this orientation, the measured ratio of emittances is about 50: $\epsilon_x \approx 0.9\mu$m, $\epsilon_y \approx 45\mu$m, with the one degree-of-freedom normalized emittance defined by $\epsilon^2 = \gamma^2(v/c)^2(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2)$. We feel that this is a good result for an initial experiment. The horizontal emittance measurement is resolution limited, as illustrated in Fig. 4 wherein a sequence of slit images is superimposed in order to form a distribution. The standard deviation of the narrow distribution is comparable to a single pixel of the CCD camera viewing the screen.

The product of the emittances is higher than that usual in operation with round beams; typically, the emittance in each transverse degree-of-freedom is about 3 to 4 μm. However, there is no reason to believe that the emittance compensation normally in use would be effective under the conditions of this experiment.

The simulations[4],[5] carried out prior to the measurements provided useful guidance, but were not perfect. The prediction of spot size just downstream of the gun worked fine. But to achieve the match to the quadrupoles, the solenoid required adjustment.

In order to obtain agreement between the location of the beam waist downstream of the booster cavity, a modification of the focusing characteristics of this device was required. In the Chambers approximation[6], its demagnification is a factor of 5, so its treatment is sensitive to a number of factors, e.g. the exact field profile. It will be worthwhile to measure the transfer matrix through the cavity experimentally.

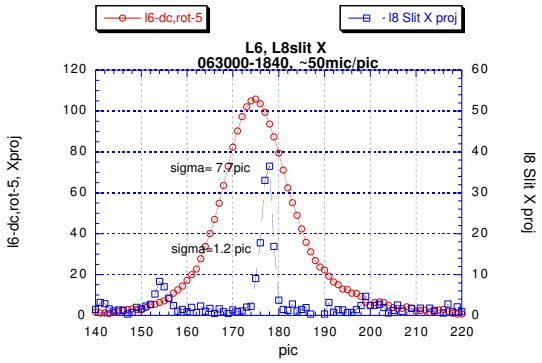

Figure 4: Projection of images used in emittance measurement at slit location and downstream of slit system.

6 CONCLUSIONS

The round-to-flat transformation has been verified, with a demonstrated emittance ratio of a factor of 50 between the two transverse degrees-of-freedom. Further work will be needed to restore the emittance compensation necessary to the delivery of low transverse emittance, and that is the subject of a follow-on experiment, in the direction suggested by Brinkmann, Debenev and Flöttmann in their EPAC2000 paper.[7] The predictive capability of the simulations is encouraging thus far, and the results reported here indicate directions for improvement.

7 ACKNOWLEGEMENTS

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8 REFERENCES

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