The “Flat Beam” Experiment at the Fermilab/NICADD Photoinjector Laboratory

A Status Report

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Origin

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

Two years ago, 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. This could be a significant step toward the elimination or simplification of the electron damping ring in a linear collider design.

When plans for the TESLA Test Facility Linac (TTFL) were developed during the years 1991-1994, the ideas on the previous page were still in the future. The first injector was a thermionic DC gun produced rather quickly at Orsay and Saclay. It delivered the high beam current of the TESLA design suitable for study of beam loading and RF control issues, though at low bunch charge.

In order to deliver the high bunch charge of the (then) TESLA design, an RF photoemission gun was selected as a second injector. Its designers, James Rosenzweig and his (then) student Eric Colby of UCLA, gave careful consideration to the thought of illuminating the cathode with a flat laser spot to achieve high transverse emittance ratio at the source. In view of the space charge concerns associated with such a design, they concluded that the next step should be a round source in view of greater confidence in performance prediction.

Two RF photoemission guns of the UCLA design were constructed at Fermilab and installed in the TTF Linac and at Fermilab in late 1998 and and the first half of 1999. During the search for reasonable operating conditions at Fermilab, a curiously squashed profile was observed on OTR screens, with major and minor axes inclined at 45 degrees to the horizontal plane.

It was not until February of 2000 that this observation was connected with the predictions in the paper by Brinkmann, Derbenev, and Flöttmann. During a brief exploration on March 2, a beam that could be truly characterized as flat in appearance was produced.

Of course, the fact that a beam looks flat does not mean that it has an interesting emittance raio, so on March 5 we proposed our experiment to the Fermilab Directorate to verify that we were indeed observing the phenomena as predicted. Authorization to proceed was soon received from Steve Holmes.

Principle

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, there are no space charge effects, and ignore the 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. 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

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \beta \\ 0 & 0 & -\frac{1}{\beta} & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ -ky_0 \\ y_0 \\ kx_0 \end{pmatrix} = \begin{pmatrix} x_0 \\ -ky_0 \\ k\beta x_0 \\ -\frac{1}{\beta} y_0 \end{pmatrix}.$$

If now we perform the match $\beta = 1/k$ 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. 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.

Brinkmann, Derbenev, and Flöttmann speak of an achievable emittance ratio of order 10^2 for a beam with normalized emittance $\sqrt{\epsilon_x \cdot \epsilon_y} \approx 10^{-6}$ m per nC of bunch charge. The resulting vertical emittance would be 0.1 mm mrad, in the range of interest for a linear collider.

Experimental 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 supercondcting booster cavity (a TESLA resonator not up to the standard for inclusion in the TESLA Test Facility) 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. This experiment operated with 0.75 kG at the cathode.

Downstream of 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 variey 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 while still getting reasonable signals from the view screens.

No modifications to the facility were needed. The principle materials cost item was liquid helium for the superconducting cavity.

Goals

1. Verify that the transformation works

2. Compare observation with simulation

3. Look for anything unexpected

Results

The transformation should work — it's linear dynamics — and it does. The match and phase difference were achieved with three skew quadrupoles. A critical observation is that the beam remained flat as it drifted downstream.

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.

From slit data, the measured ratio of emittances is about 50: $\epsilon_y \approx 1.3\mu$m, $\epsilon_x \approx 70\mu$m. The measurement is limited by resolution of the diagnostics employed. We feel that this is a good result for an initial experiment.

The product of the emittances is higher than that usual in A0 operation with round beams. However, there is not reason to believe that the emittance compensation normally in use would be valid under the conditions of this experiment.

The simulations by Flöttmann and Nagaitsev 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 put into the simulations. In the Chambers approximation, 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.

The one observation that qualifies as a surprise was a decrease in quantum efficiency of the cathode and dark current in the course of the experiment. Walter Hartung noticed this while doing gun studies just after two continuous weeks of our measurements in May. He observed if he restored the field on the cathode to zero and continued to operate the laser, the quantum efficiency recovered in two hours.

This behavior is not understood.

Plans

When we felt that the transformation had been confirmed, we requested and rceived approval for a follow-on experiment. In their paper presented at the last year's EPAC conference in Vienna, Brinkmann, Derbenev and Flöttmann predict that the combination of a long laser pulse (to reduce space charge effects at constant bunch charge) and a tailored solenoid field profile (to effect emittance compensation) will produce a significant improvement over the first experiment.

This step requires modification of the laser to stretch the pulse length while maintaining sufficient energy in the UV to produce a ≈ 1 nC bunch. Last Autumn, the pulse was extended to 30 ps, however beam has not yet been produced in that configuration. Meanwhile, we hope to measure the transfer matrix of the booster cavity and improve the resolution of the emittance diagnostics.

Concluding Remarks

For a linear collider, a polarized electron beam is desired. Current designs employ polarized DC guns as sources, and, if a linear collider project were funded this afternoon, that is what would be used. Production of a beam that is both polarized and flat from the source is a a non-trivial R&D effort and these two aspects can be pursued separately to a large extent.

But even without polarization, a flat beam produced along the lines sketched above may be useful for other purposes, and two possibilities appear in this afternoon's agenda. Understanding of the process would benefit from study at other locations; in this connection, the proposal by David Yu and collaborators for an experiment based on an S-Band PWT gun should be noted.