ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK072

# GENERATION OF FLAT ULTRA-LOW EMITTANCE BEAMS

N. Bell, UCLA Department of Physics and Astronomy, Los Angeles, CA, USA
L. Phillips, UCLA Department of Physics and Astronomy, Los Angeles, CA, USA

*Abstract*

By placing a cathode in a longitudinal magnetic field generated by a solenoid or permanent magnet, angular-momentum dominated electron beams can be produced. Such beams can be uncoupled using a skew-quadrupole channel to remove the angular momentum and yield flat beams with an ultralow emittance in one of the transverse dimensions. Flat beams have immediate relevance in our pursuit of ultrahigh brightness in two dimensions for dielectric laser accelerator (DLA) or slab beam applications. We are currently investigating the possibility of implementing flat beam generation at the UCLA Pegasus beamline. We utilize particle tracking simulations to optimize the transverse emittance ratio and normalized transverse emittance. Our simulations show emittance ratios of more than 100 and normalized emittances in the <5 nm range in the vertical dimension, matching analytic estimates. In addition to simulation results, experimental plans to implement and test the flat beam transform (FBT) are also discussed.

## INTRODUCTION

An axially symmetric angular momentum dominated beam can be transformed into a flat beam by applying an optical transformation to remove the angular momentum. An angular momentum dominated beam is produced by generating particles from a cathode which is immersed in a longitudinal magnetic field due to a solenoid or permanent magnet. Following [1, 2], as the particles leave the magnetic field and pass through the fringe field, they gain mechanical angular momentum which is related to the field amplitude at the cathode $B$ and the initial spotsize $\sigma_x$:

$$L = \kappa_0 \sigma_x^2 \tag{1}$$

where $\kappa_0 = \frac{eB}{2m_0c}$. The angular momentum can then be removed using a channel of three skew quadrupoles to remove the x-y correlation resulting in final emittances given by

$$\epsilon_\pm = \sigma_x \sqrt{\frac{MTE}{m_0c^2} + (\kappa_0\sigma_x)^2} \pm L \tag{2}$$

where MTE is the mean transverse energy [3]. It is immediately apparent that by closely matching in magnitude the first and second terms in Eq. (2), we can produce one very small and one very large emittance [4].

In order to split the transverse emittances, the beam must be send through a skew quadrupole triplet. The 4x4 transformation matrix through three normal thin lens quadrupoles is of the block diagonal form

$$M = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix} \tag{3}$$

Table 1: FBT Simulation Parameters

| Parameters | No Space Charge | 20 fC Space Charge |
|---|---|---|
| Spotsize | 40 µm | 40 µm |
| Cathode B-Field | 0.32 T | 0.32 T |
| Quad Effective Length | 10.5 cm | 10.5 cm |
| Quad Spacing | 2.5 cm, 5 cm | 2.5 cm, 5 cm |
| Skew Quad Gradients | 1.1690, -2.0457, 2.8785 T/m | 1.1628, -2.0641 3.0241 T/m |
| Focusing Quad Gradients | -3.50, 1.28 T/m | -3.50, 1.28 T/m |
| X Std Dev At 4 m | 1.47 mm | 1.45 mm |
| Y Std Dev At 4 m | 3.74 µm | 3.84 µm |
| Large Emittance | 280 nm | 282 nm |
| Small Emittance | 2.24 nm | 2.26 nm |
| Emittance Ratio | 125 | 124 |

where A and B are 2x2 matrices depending of the quadrupole focusing strengths and drift distances. We can apply a rotation to this matrix to get the transformation matrix of a skew quadrupole channel

$$M = \frac{1}{2} \begin{bmatrix} A_+ & A_- \\ A_- & A_+ \end{bmatrix} \tag{4}$$

where $A_\pm = A \pm B$. Now we must just find the correct quadrupole strengths which will remove the beam's angular momentum, which corresponds to block diagonalizing the beam matrix. Solving this problem, we arrive at the matrix equation

$$A_+S = A_- \tag{5}$$

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK072

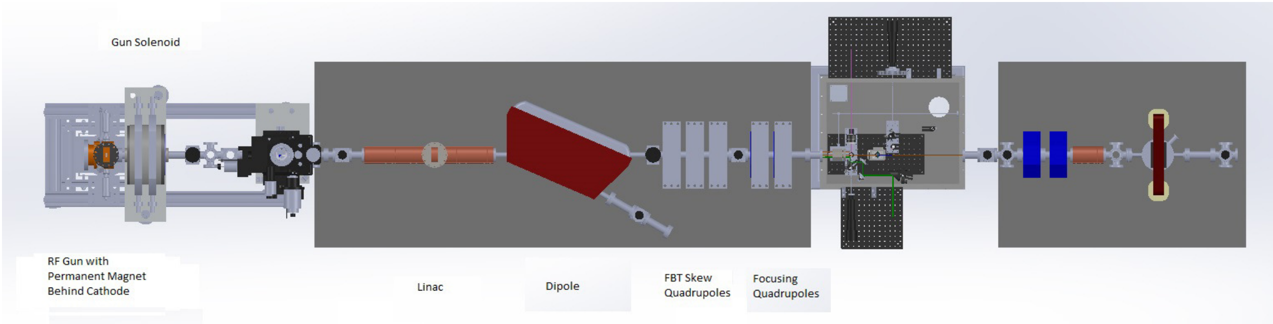


Figure 1: A diagram of the Pegasus beamline including FBT quadrupoles.

where $S$ is the symplectic matrix

$$S = \begin{bmatrix} -\alpha & -\beta \\ (1+\alpha^2)/\beta & \alpha \end{bmatrix} \quad (6)$$

with $\alpha$ and $\beta$ being the Twiss parameters of the incoming beam. Then, solving Eq. (5) for the quadrupole strengths, we get

$$q_1 = \pm\sqrt{\frac{-d_2 S_{11} + S_{12} - d_2 d_T S_{21} + d_T S_{22}}{d_2 d_T S_{12}}} \quad (7)$$

$$q_2 = -\frac{S_{12} + d_T S_{22}}{d_2 d_3 (1 + S_{12} q_1)} \quad (8)$$

$$q_3 = -\frac{q_1 + q_2 + d_2 S_{11} q_1 q_2 + S_{21}}{1 + (d_T q_1 + d_3 q_2) S_{11} + d_2 d_3 q_2 (S_{21} + q_1)} \quad (9)$$

where $d_2$ and $d_3$ are the drift lengths and $d_T = d_2 + d_3$. This quadrupole setup is what is referred to as the flat beam transform and has already been demonstrated at Fermilab [5, 6]. Fig. 1 contains a diagram of the Pegasus beamline showing implementation of the round to flat beam transformer. These thin lens solutions are the starting point from which we run our simulations using the General Particle Tracer (GPT) software.

## SIMULATIONS

Particle simulations have been run in GPT in order to verify the plausibility of implementing the FBT technique at the Pegasus beamline, as well as to gain a better understanding of how variables such as drift length and beam charge affect the effectiveness of the transform. MATLAB was used to call GPT, so as to give us access to a more robust optimization toolbox than is available within GPT. Originally simulations were run without space charge and using hard edge quadrupole fields. The quadrupole gradients we find for simulated thick lens quadrupoles are always quite different from the theoretical thin lens solution, but the final achieved emittances always match up closely with theory. Once viable solutions were found, realistic fringed quadrupole fields were simulated using a GPT custom element and space charge was included. Table 1 contains a list of the parameters and the associated skew quadrupole solutions for our current FBT configuration. We can see that, for a field on the cathode of 0.32 T and a cathode thermal emittance of 25.1 nm, we can achieve a lower emittance of around 2.24 nm with a ratio of 125 even with 20 fC of charge, aligning closely with the predicted theoretical values ($\epsilon_- = 2.19$ nm, $\epsilon_+ = 302$ nm, $\epsilon_+/\epsilon_- = 138$). This $\epsilon_-$ is an order of magnitude smaller than what has been previously achievable at the Pegaus beamline [7]. Also of interest is the ability to focus the beam in the y-direction down to a width of a few microns, which has relevance for the possible future application of feeding the beam into a DLA [8].

In Fig. 2 and Fig. 3, we show a demonstration of how the FBT manipulates the individual trace spaces. The overall effect is an enlarging of the trace space area in the x-coordinate and a simultaneous dramatic shrinking of the trace space area in the y-coordinate.

Additionally, we explored the effects of space charge on the smallest emittance. The results of this simulation are plotted in Fig. 4. We can see that, up to around 30 fC, there is very little increase in $\epsilon_-$ and that the smaller emittance remains under 3 nm all the way up to 100 fC of beam charge.

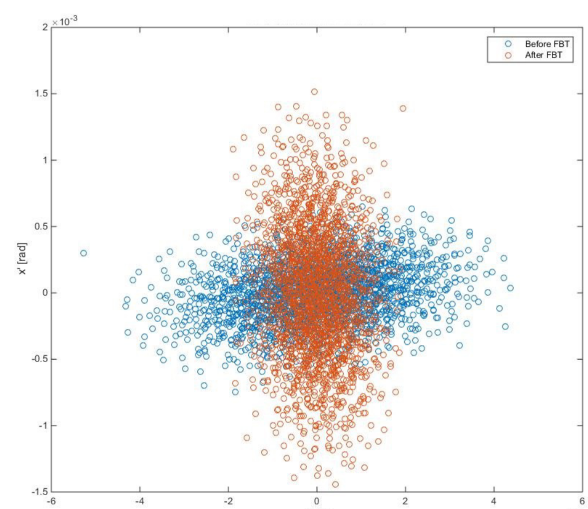


Figure 2: X-coordinate trace space for FBT with a 0.32 T field on the cathode.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK072



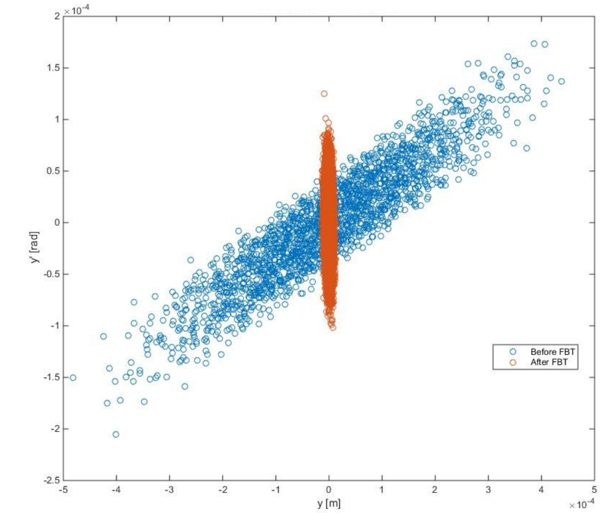


Figure 3: Y-coordinate trace space for FBT with a 0.32 T field on the cathode.

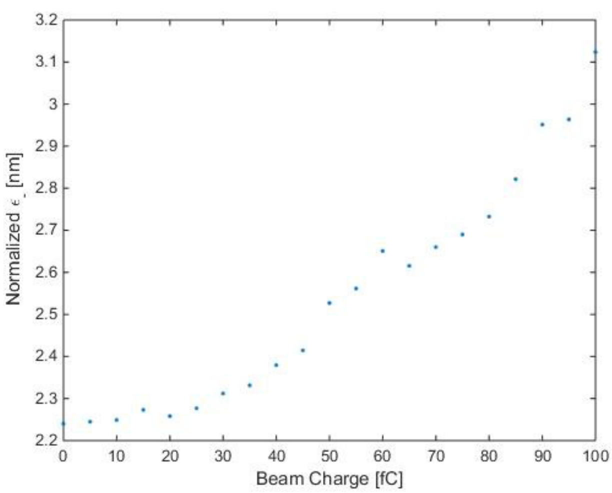


Figure 4: Emittance vs. Beam Charge up to 100 fC.

## EXPERIMENTAL PLAN

Our plan is to implement the flat beam transformer in the Pegasus beamline in the near future. For initial runs, the field on the cathode will be produced by a permanent magnet affixed to the back of a copper cathode. There are plans to look into replacing the permanent magnet with a solenoid soon, to provide more experimental flexibility. The FBT setup will consist of three skew quadrupoles followed by two normal quadrupoles which will be used to focus the beam.

The initial settings for the FBT will come from our GPT simulations. From there, the beam flatness will be optimized and final emittance measurements will be made using a quadrupole scan utilizing the two focusing quadrupoles, as well as two other quadrupoles that are already present in the beamline after the FBT.

## CONCLUSIONS

The UCLA Pegasus beamline is capable of producing flat beams in the sub 5 nm range that can be used in a variety of beam studies. Our goal is to have a functioning FBT setup in the next year.

## ACKNOWLEDGEMENTS

This work is supported by the National Science Foundation under Grant No. 1549132 and the Gordon and Betty Moore Foundation under award GBMF4744.

## REFERENCES

[1] Y.-E Sun, [Ph.D. thesis] University of Chicago (2005).

[2] A. Ody, P. Musumeci, J. Maxson, D. Cesar, R.J. England, K.P. Wootton, Nuclear Instruments and Methods in Physics Research A, Pages 75-83 (2016).

[3] Ivan V. Bazarov, Bruce M. Dunham, K. Charles, Sinclair Phys. Rev. Lett. 102 (2009) 104801.

[4] R. Brinkmann, Y. Derbenev, K. Floettmann, Phys. Rev. ST Accel. Beams 4 (2001) 053501.

[5] P. Piot, Y.-E. Sun, K.-J. Kim, Phys. Rev. ST Accel. Beams 9 (2006) 031001.

[6] Y.-E. Sun, P. Piot, K.-J. Kim, N. Barov, S. Lidia, J. Santucci, R. Tikhoplav, J. Wennerberg, Phys. Rev. ST Accel. Beams 7 (2004) 123501.

[7] D. Cesar, J. Maxson, P. Musumeci, Y. Sun, J. Harrison, P. Frigola, F.H. O'Shea, H. To, D. Alesini, R.K. Li, Phys. Rev. Lett. 117 (2016) 024801.

[8] P. Musumeci, J.T. Moody, C.M. Scoby, M.S. Gutierrez, M. Westfall, R.K. Li, J. Appl. Phys. 108 (11) (2010) 114513.